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Title: LUNA Condition-Based Monitoring Update: Auto-encoders on Actuator Data

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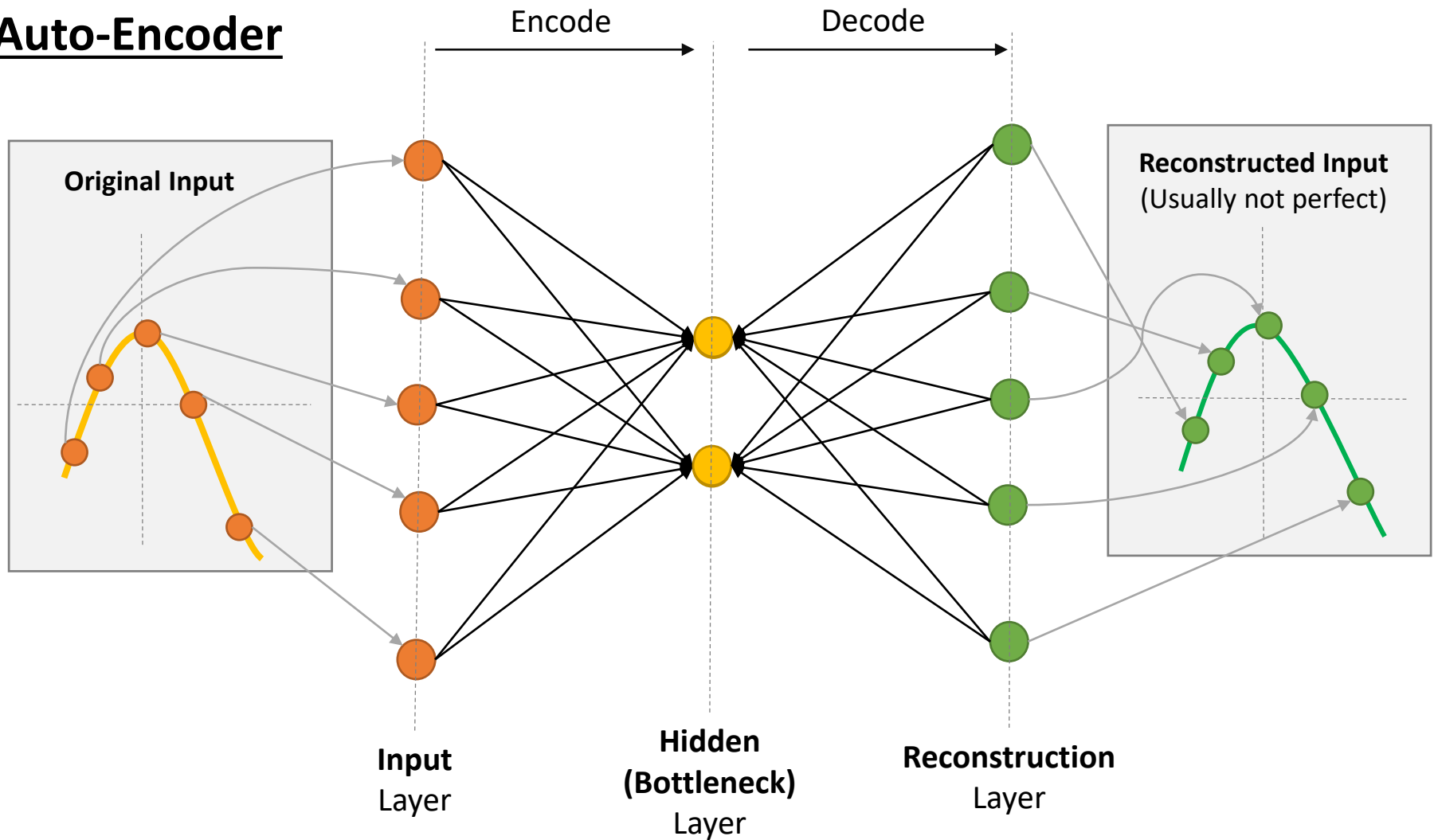
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LUNA Condition-Based Monitoring Update:

Auto-encoders on Actuator Data

Presented 4/20/2021

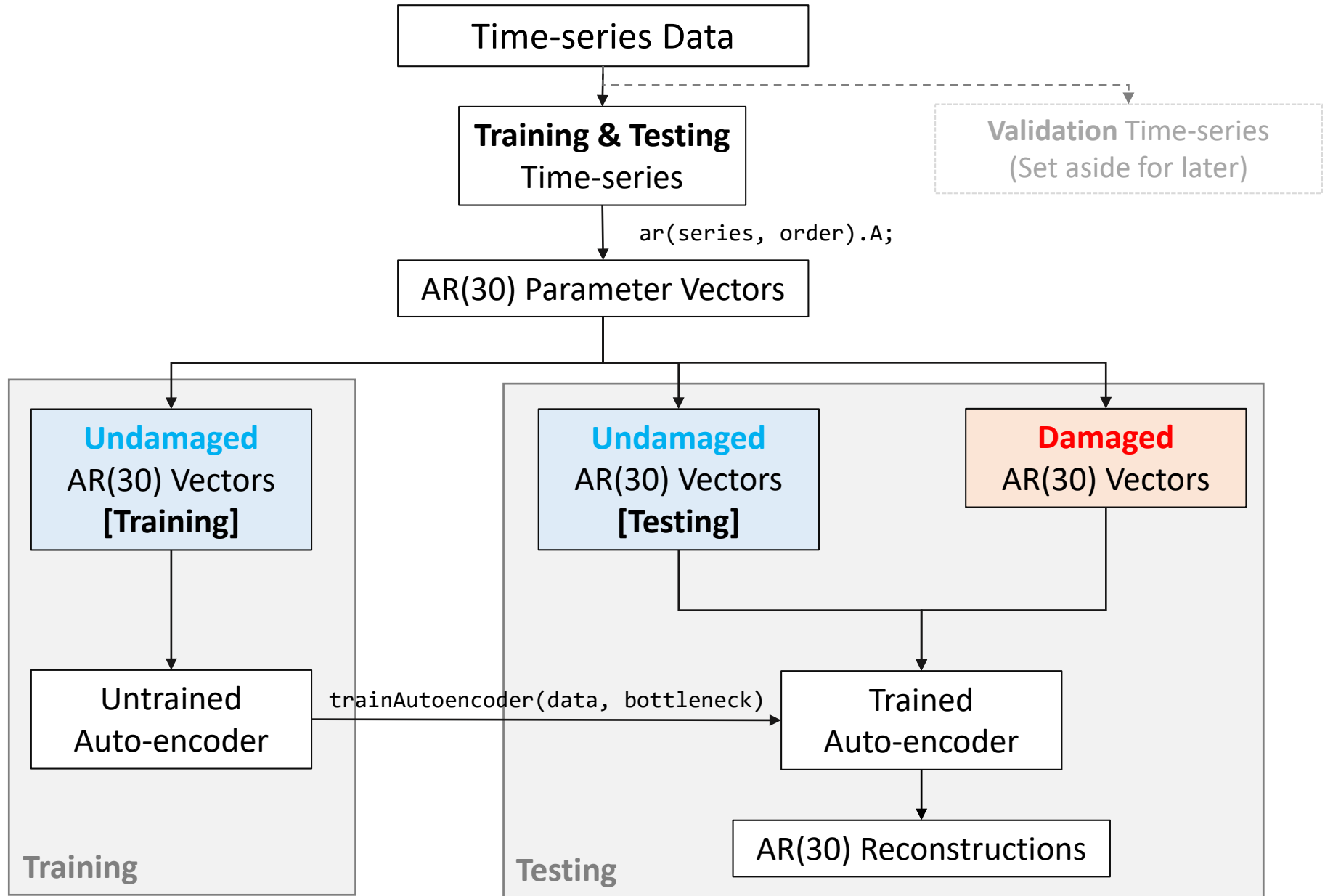
Auto-Encoder



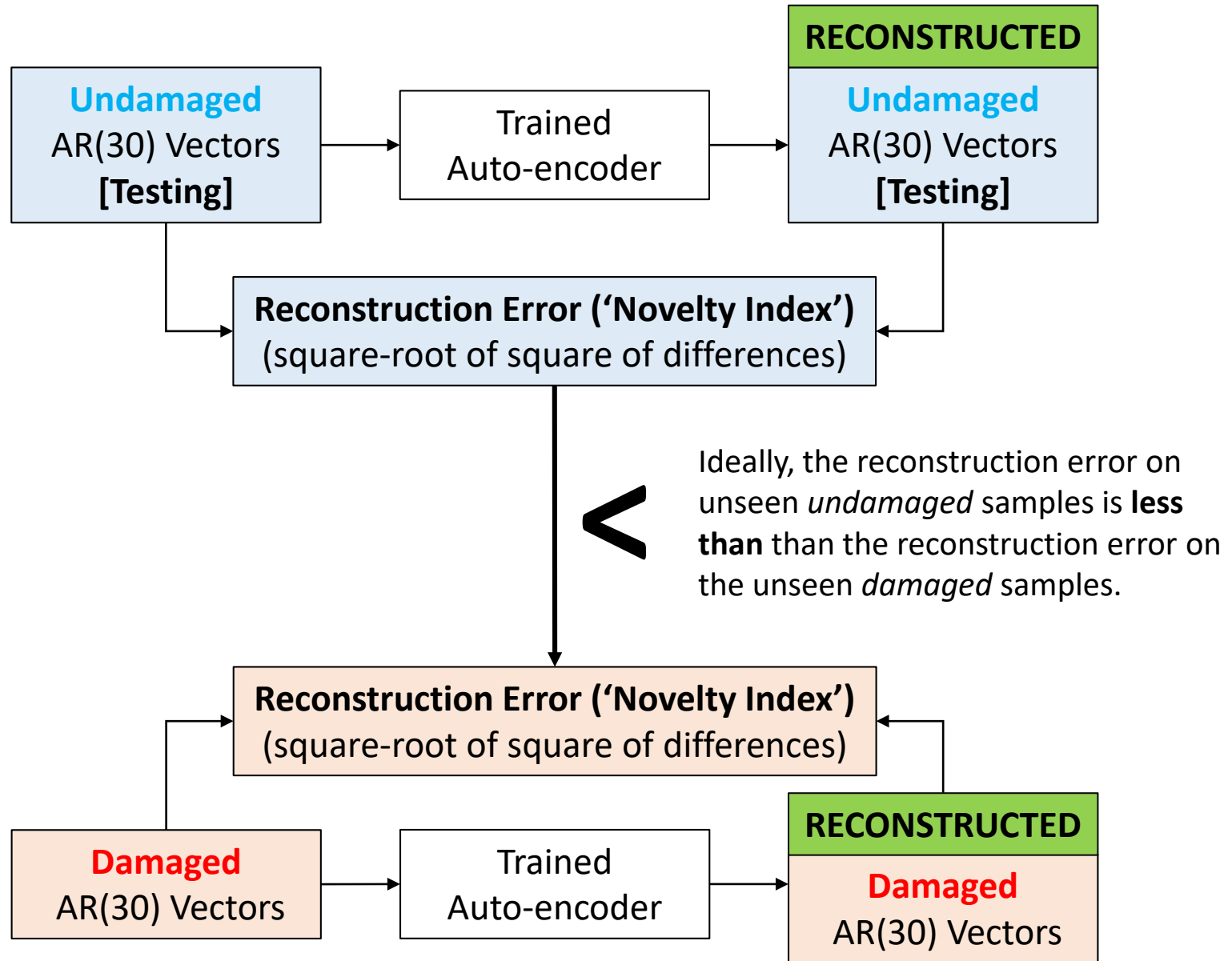
An auto-encoder is a neural network trained to output a reconstruction of its input. There is a 'bottleneck' layer whose dimension is typically lower than that of the input.

Because the input passes through the bottleneck, the auto-encoder must learn to compress (encode) the input into this low-dimensional form, and to decompress (decode) the compressed data into a close approximation of its original form.

Auto-encoders for Anomaly Detection [1/2]



Auto-encoders for Anomaly Detection [2/2]

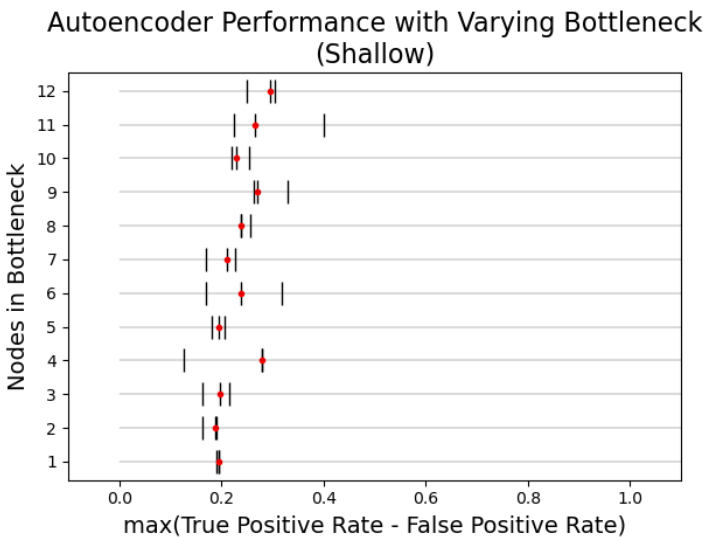


Bottleneck Optimization Performance Summary

True Positive: The reconstruction error for a sample is above a threshold and the sample is damaged.

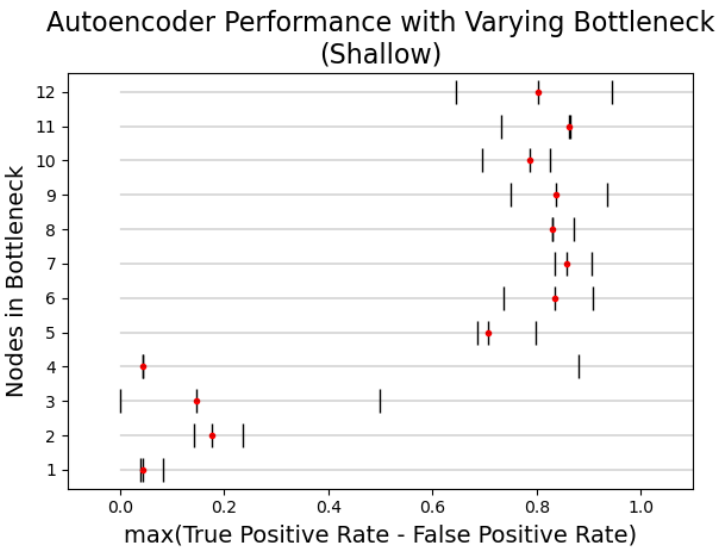
All Actuators

Shallow

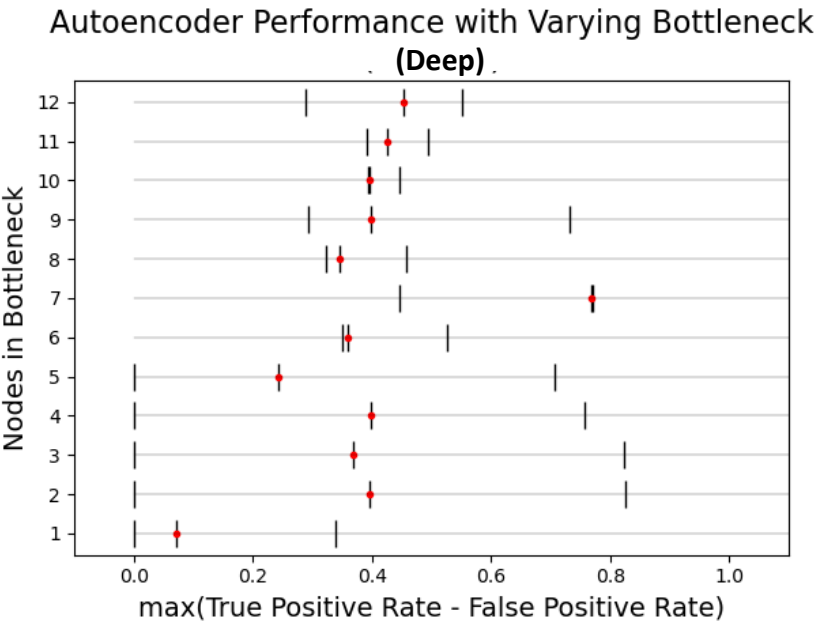
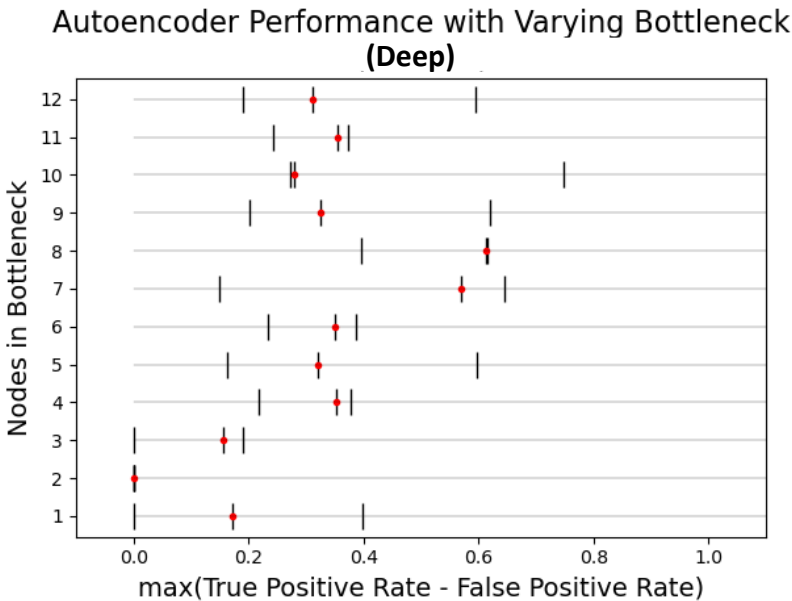


Only Board 401 Data

Shallow



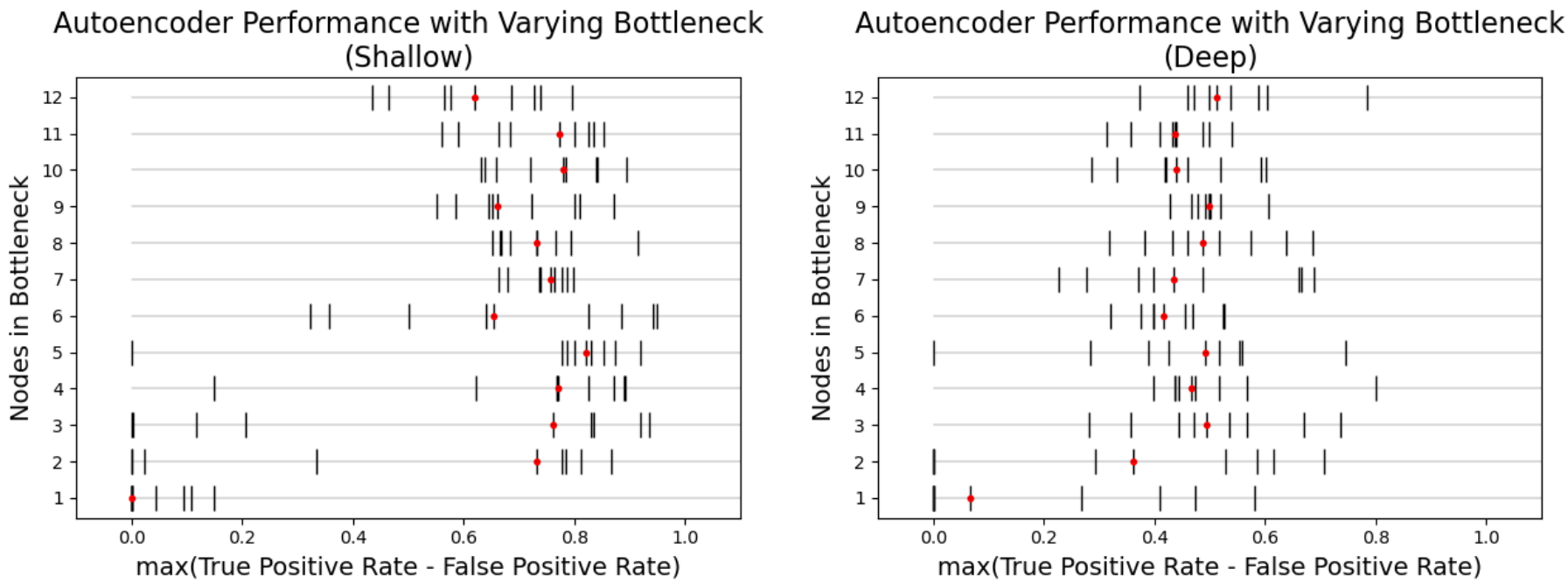
Deep



These graphs use 3-fold validation.

Bottleneck Optimization Performance Summary

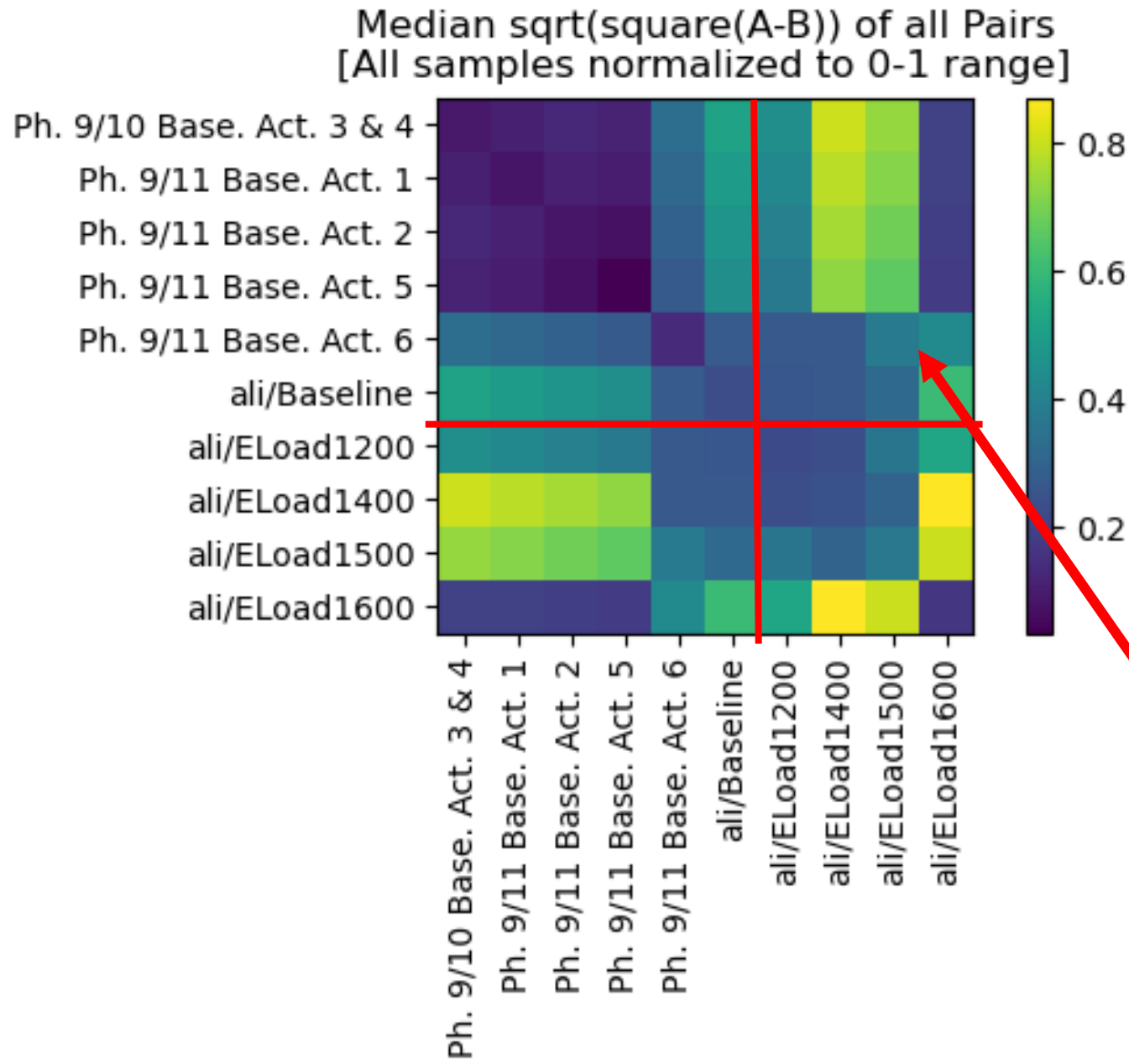
Just Board 401 Data



Both deep and shallow appear to do better when not using the Philadelphia data to supplement the baseline data under the current method of normalization.
So far the shallow networks appears to perform slightly better.

These graphs use 9-fold cross validation.

Between-Class and Within-Class Median sqrt(square(differences)))



If the reconstruction error is above ~0.2, then the error in reconstruction is greater than difference between some damaged and undamaged classes.

ELoad1600 and the Philadelphia datasets are surprisingly similar.

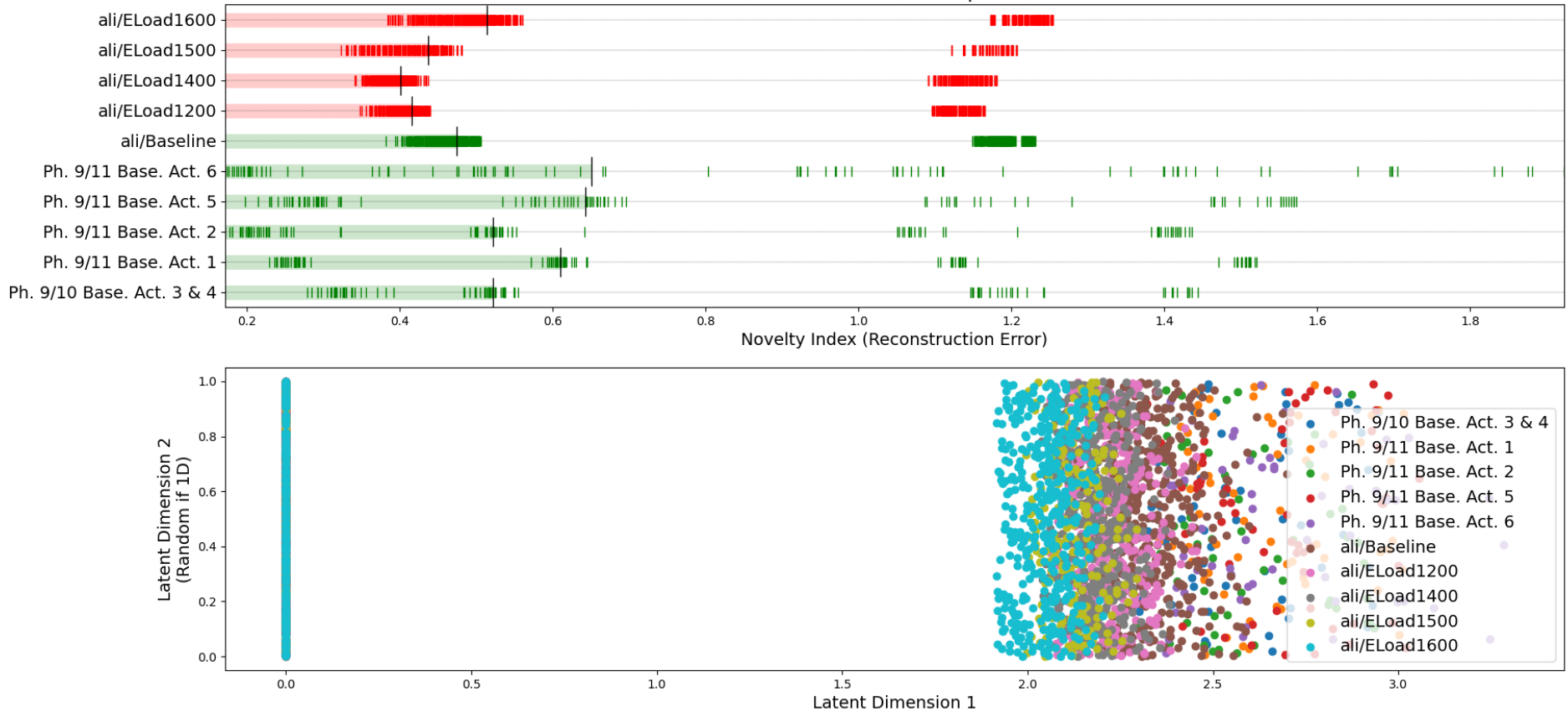
This may be due to the normalization scheme used (global min/max, normalized to 0-1 range).

The top-right quadrant (mirrored by bottom left) shows the median differences between undamaged and damaged classes.

Multi-Actuator Shallow Auto-encoder

Multi-Actuator Data | Bottleneck of 1

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 1, 100 Epochs, 9 Fold Stratified



All of the following graphs use 9-fold* stratified cross-validation.

Each consists both of a separate training & testing set and an auto-encoder.

Each fold has approximately 1039 training samples and 377 testing samples.

Because the 9 auto-encoders are trained separately, it's possible for them to learn different methods for reconstructing the data.

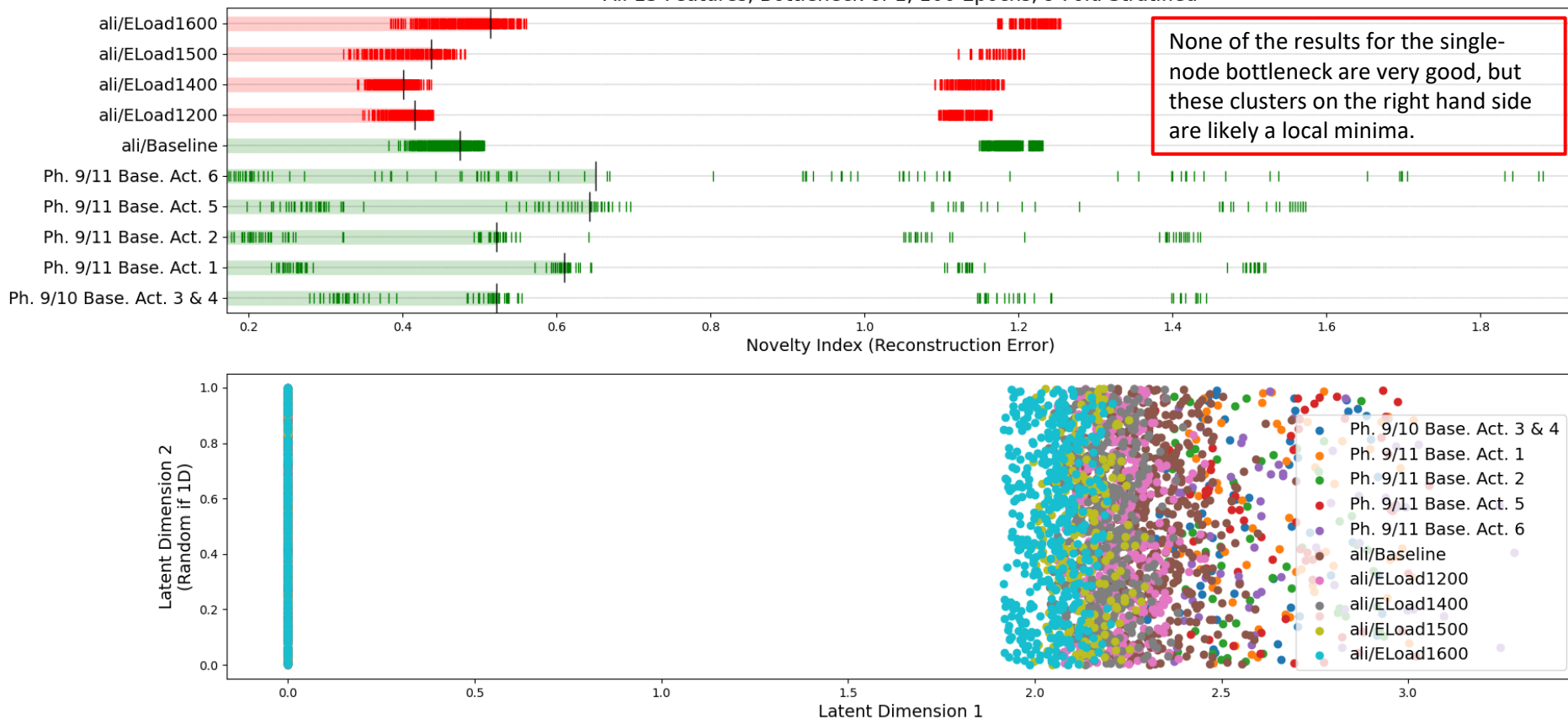
Sometimes the auto-encoder will get stuck in local minima, and perform poorly.

It's also possible the auto-encoder is learning a good representation, but one that doesn't produce different magnitude reconstruction errors for damaged/undamaged inputs.

**9-Fold was selected because 1/10th of the data has been set aside for eventual validation.*

Multi-Actuator Data | Bottleneck of 1

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 1, 100 Epochs, 9 Fold Stratified



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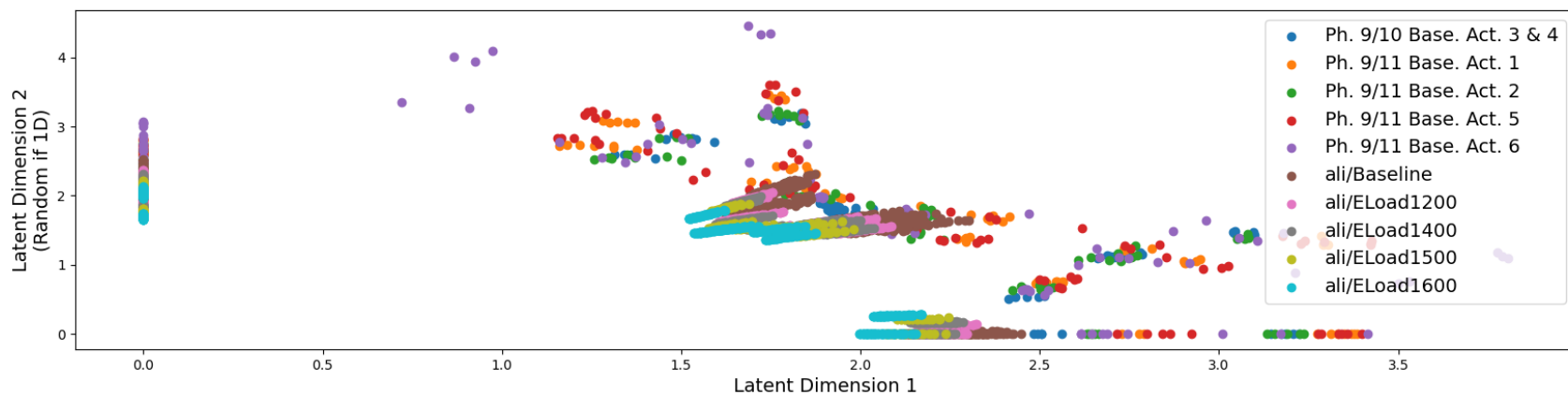
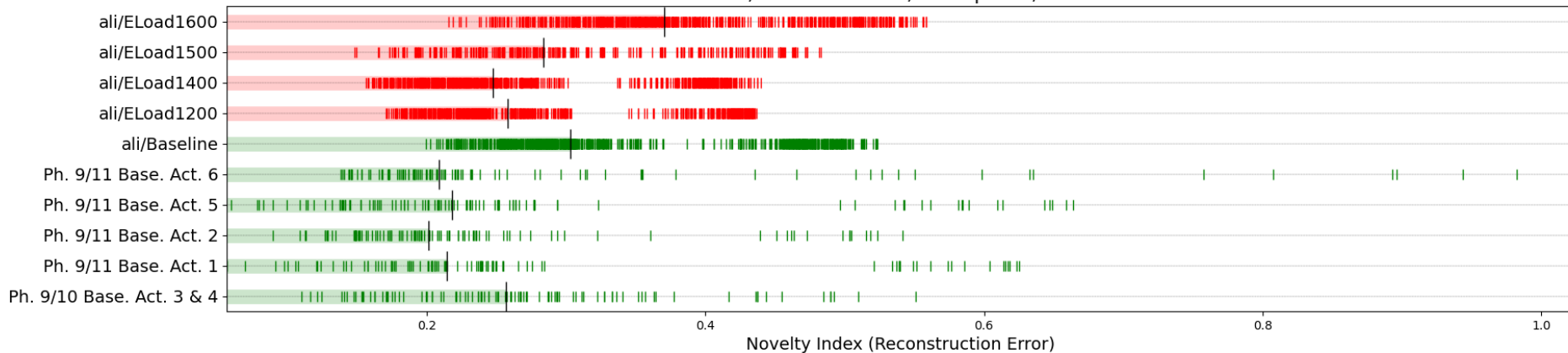
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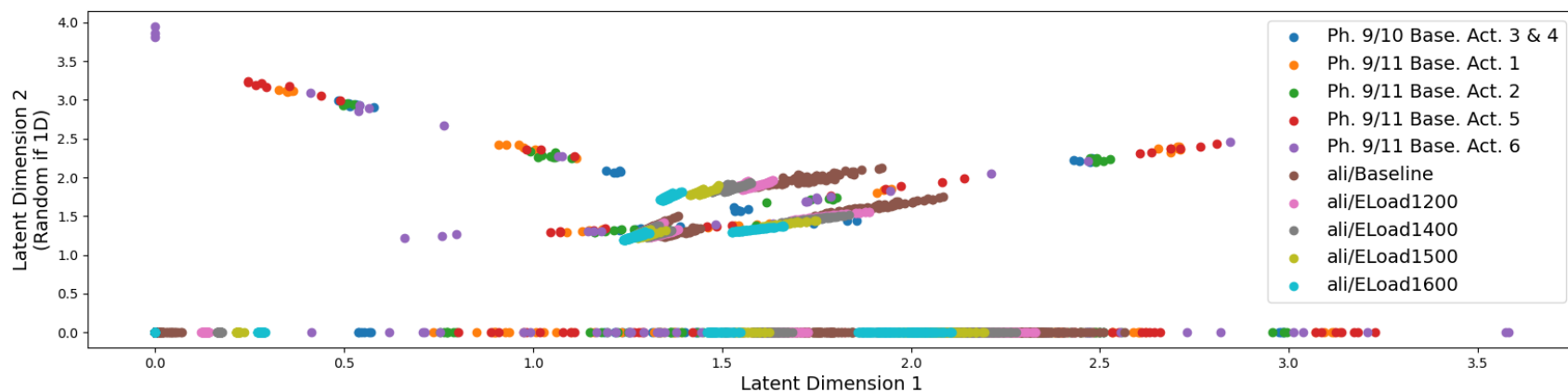
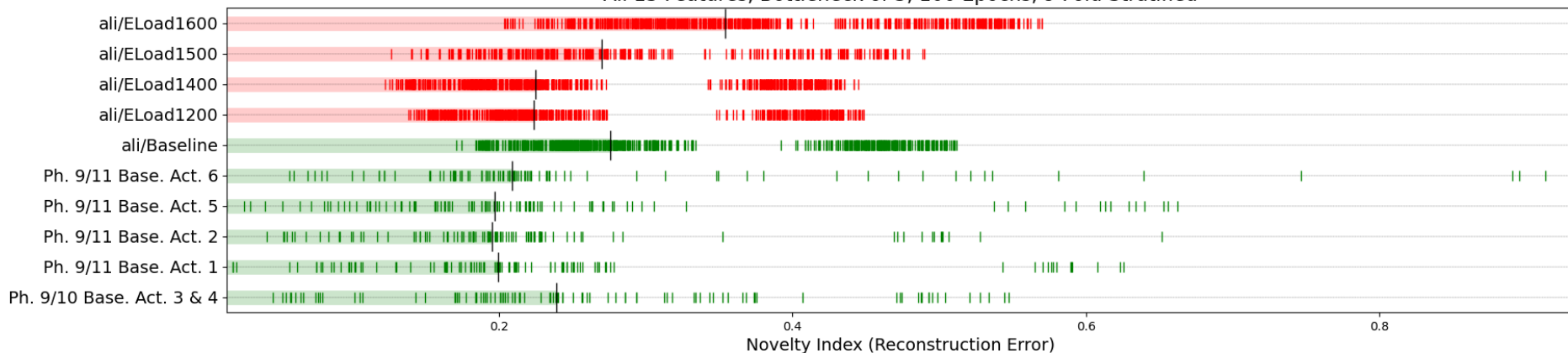
Multi-Actuator Data | Bottleneck of 2

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 2, 100 Epochs, 9 Fold Stratified



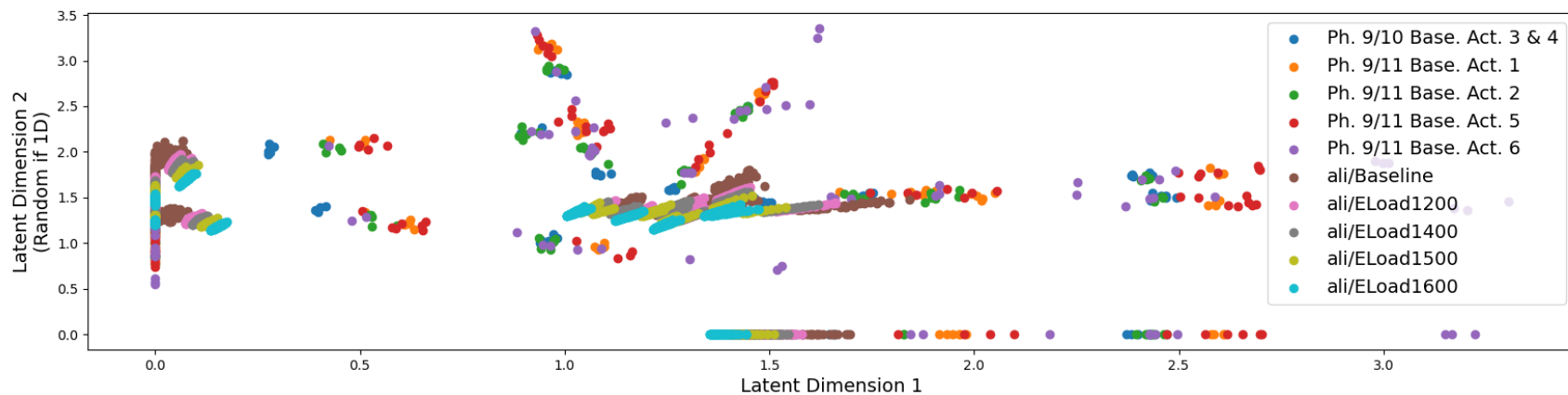
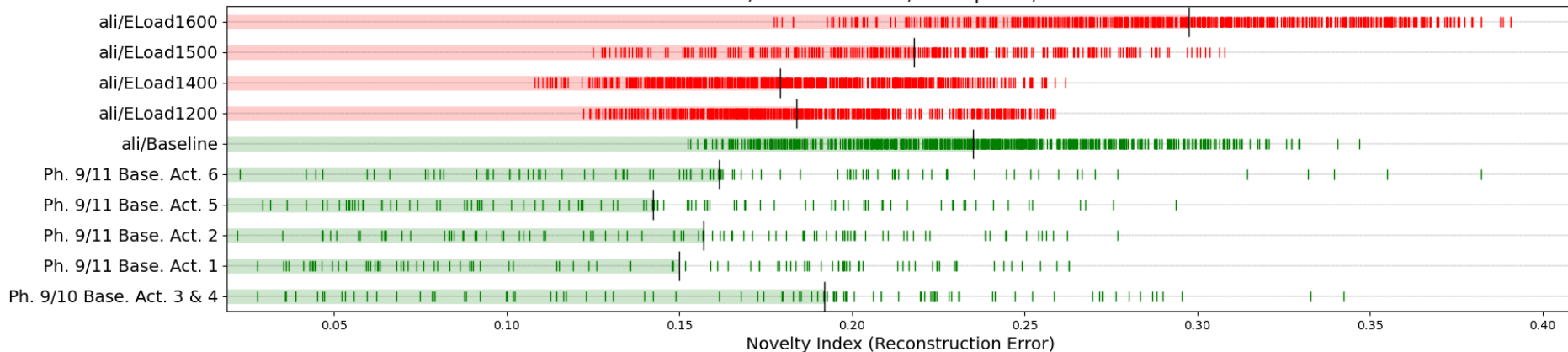
Multi-Actuator Data | Bottleneck of 3

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 3, 100 Epochs, 9 Fold Stratified



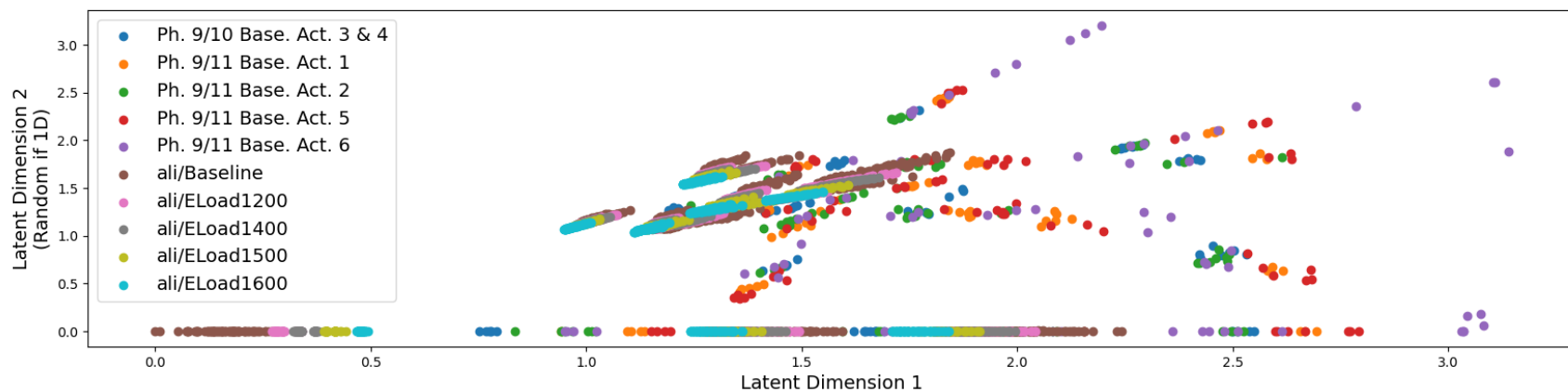
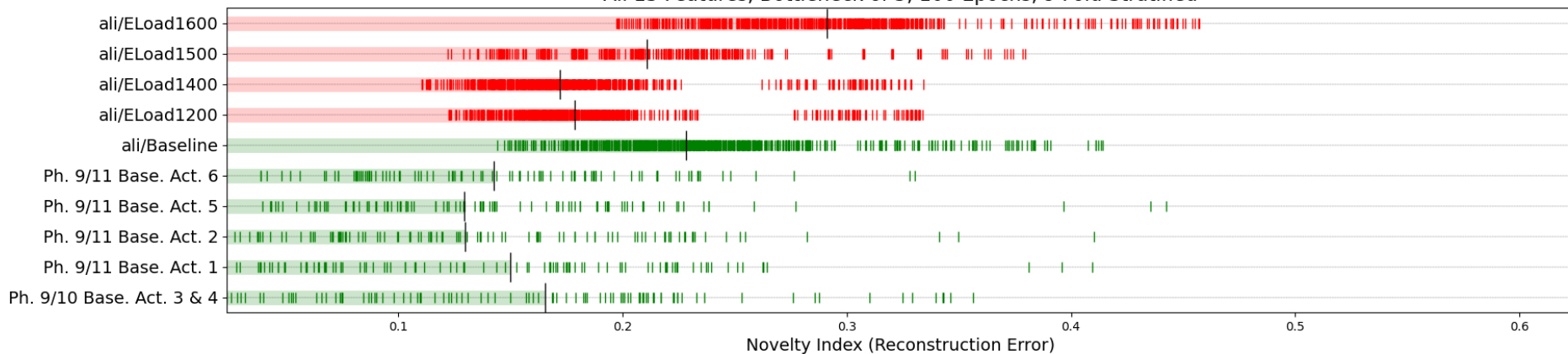
Multi-Actuator Data | Bottleneck of 4

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 4, 100 Epochs, 9 Fold Stratified



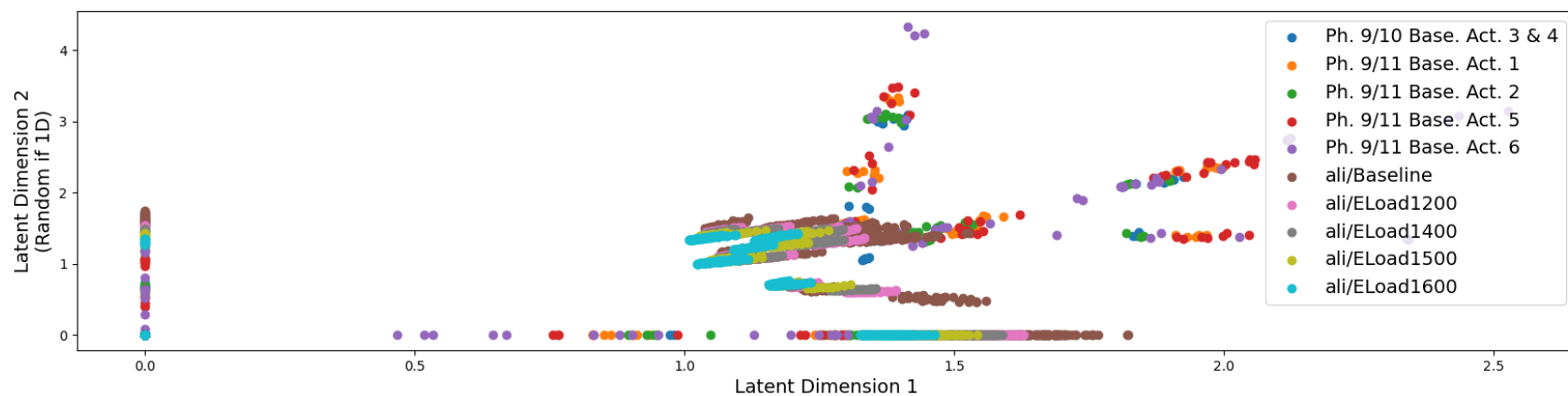
Multi-Actuator Data | Bottleneck of 5

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 5, 100 Epochs, 9 Fold Stratified



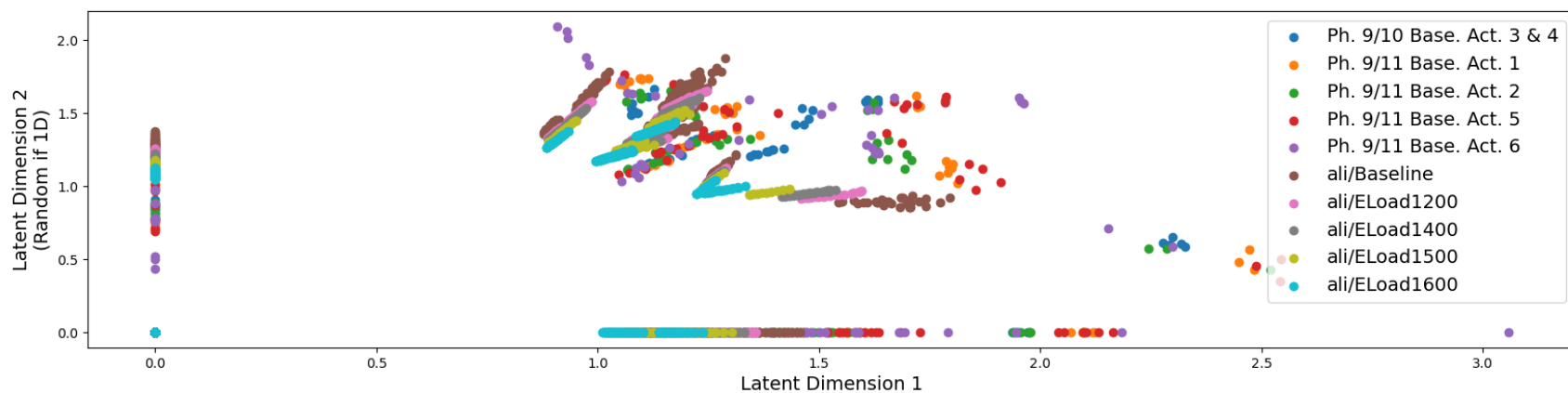
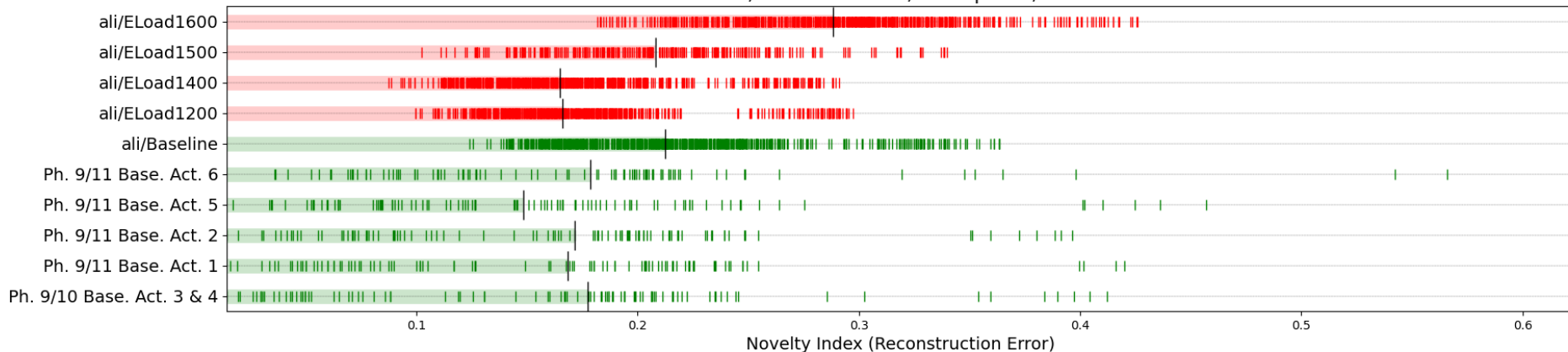
Multi-Actuator Data | Bottleneck of 6

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 6, 100 Epochs, 9 Fold Stratified



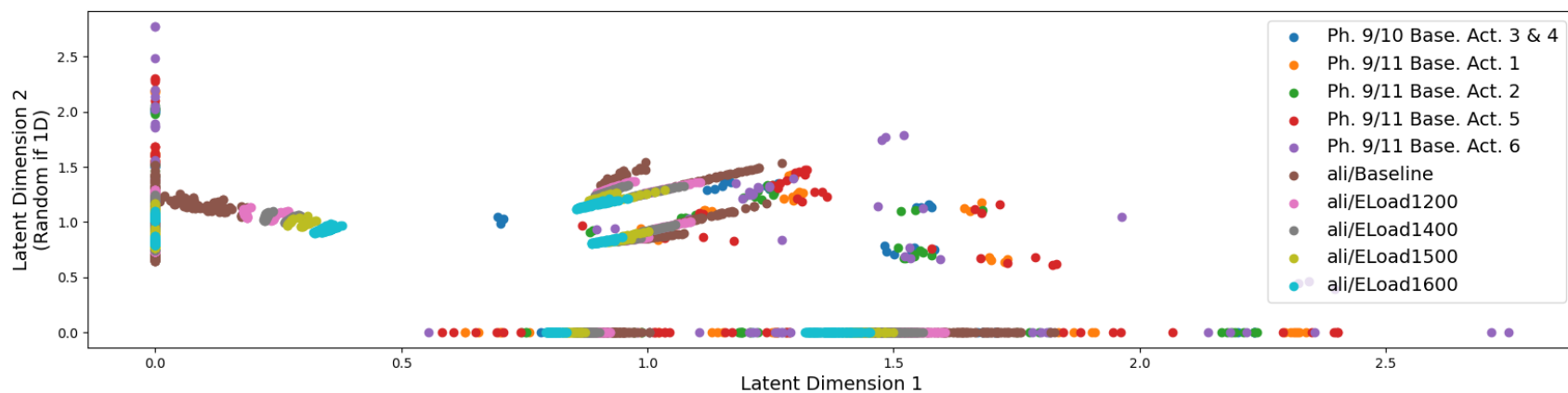
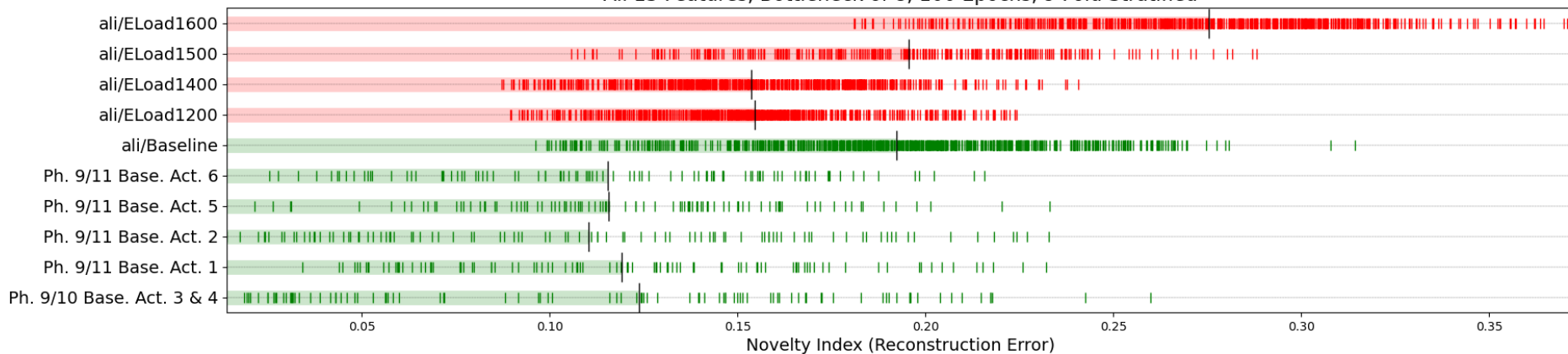
Multi-Actuator Data | Bottleneck of 7

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 7, 100 Epochs, 9 Fold Stratified



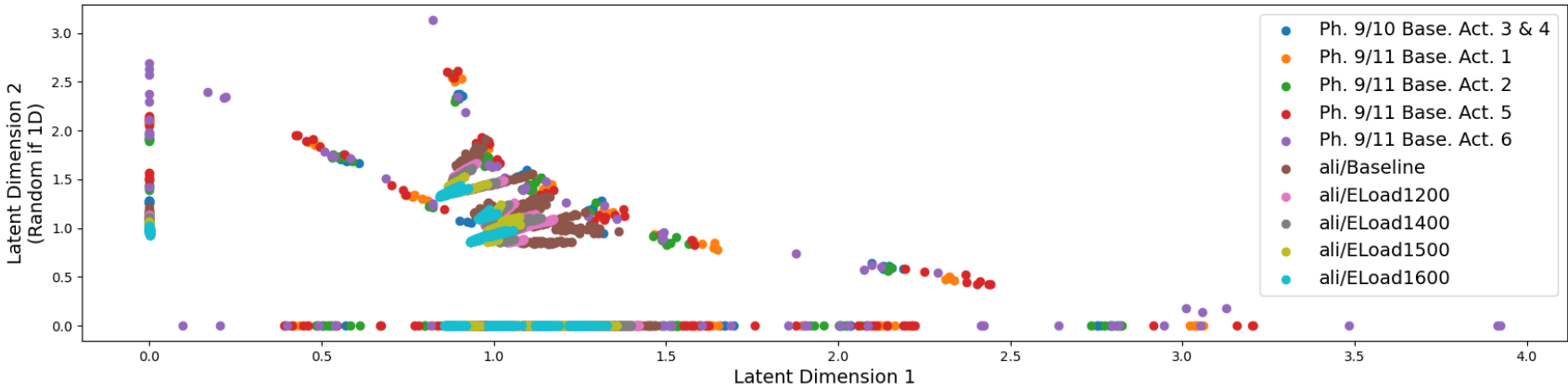
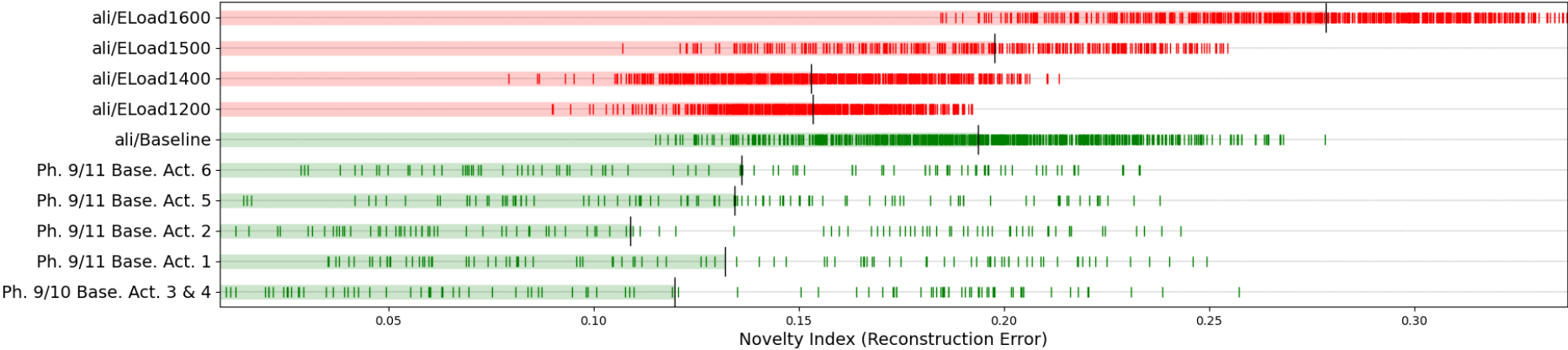
Multi-Actuator Data | Bottleneck of 8

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 8, 100 Epochs, 9 Fold Stratified



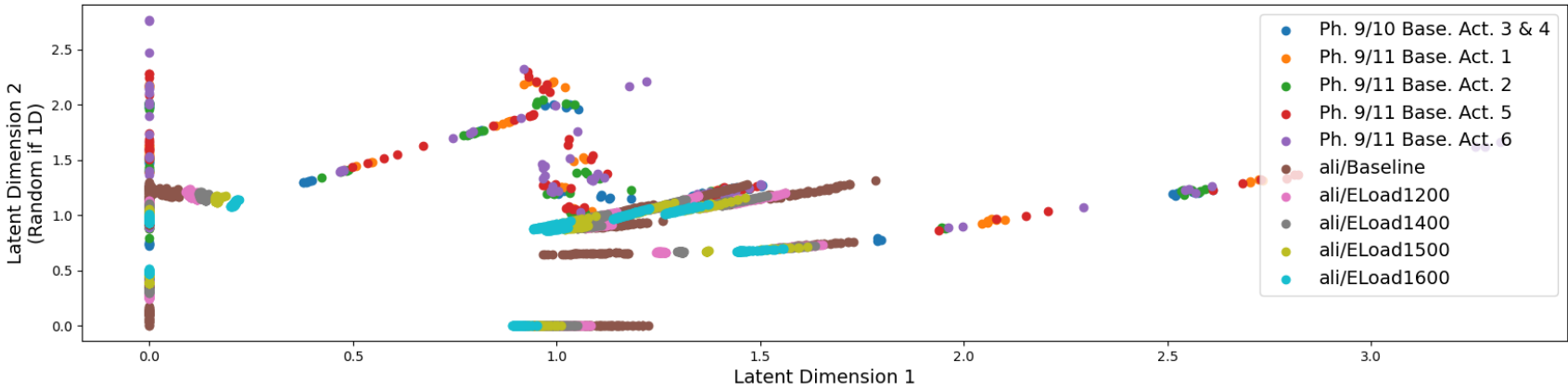
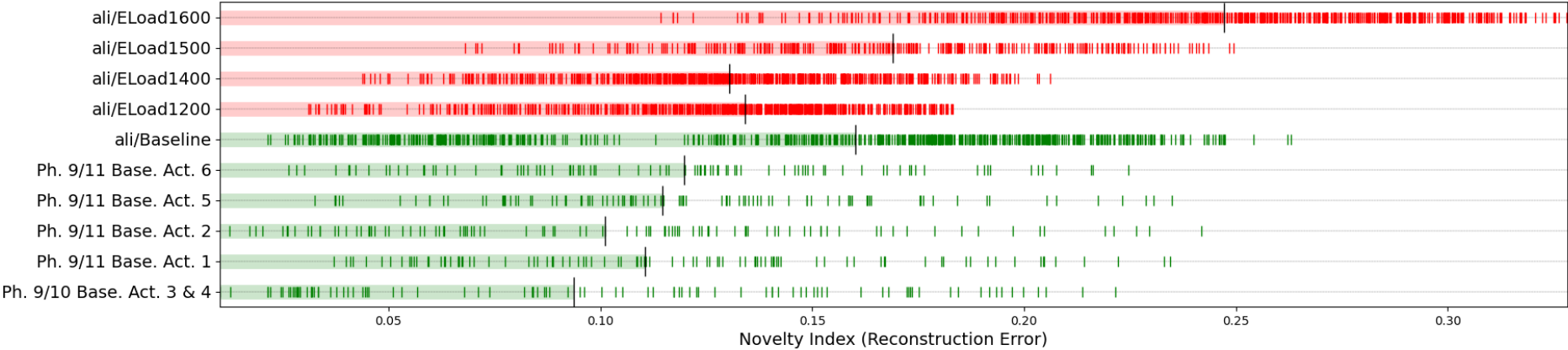
Multi-Actuator Data | Bottleneck of 9

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 9, 100 Epochs, 9 Fold Stratified



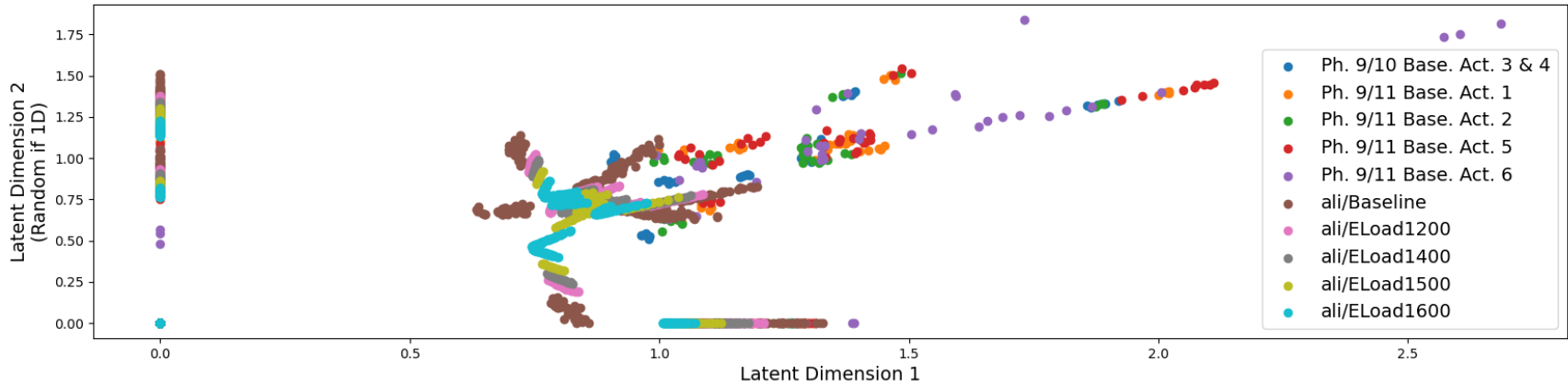
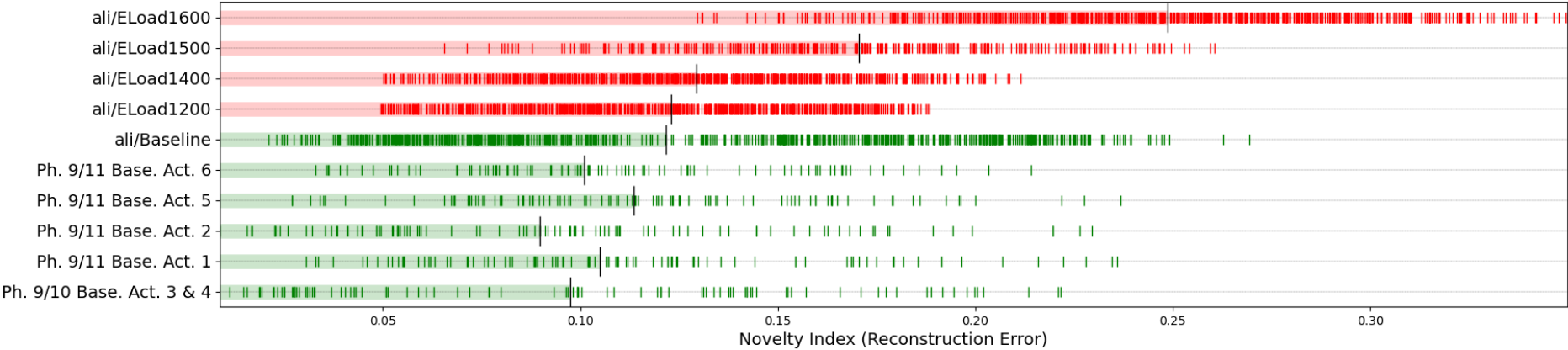
Multi-Actuator Data | Bottleneck of 10

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 10, 100 Epochs, 9 Fold Stratified



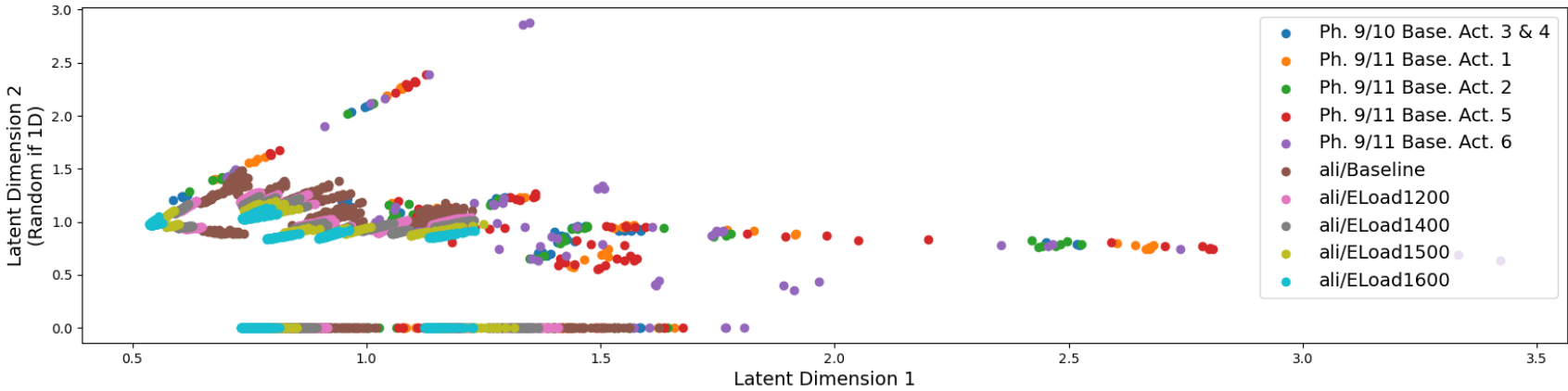
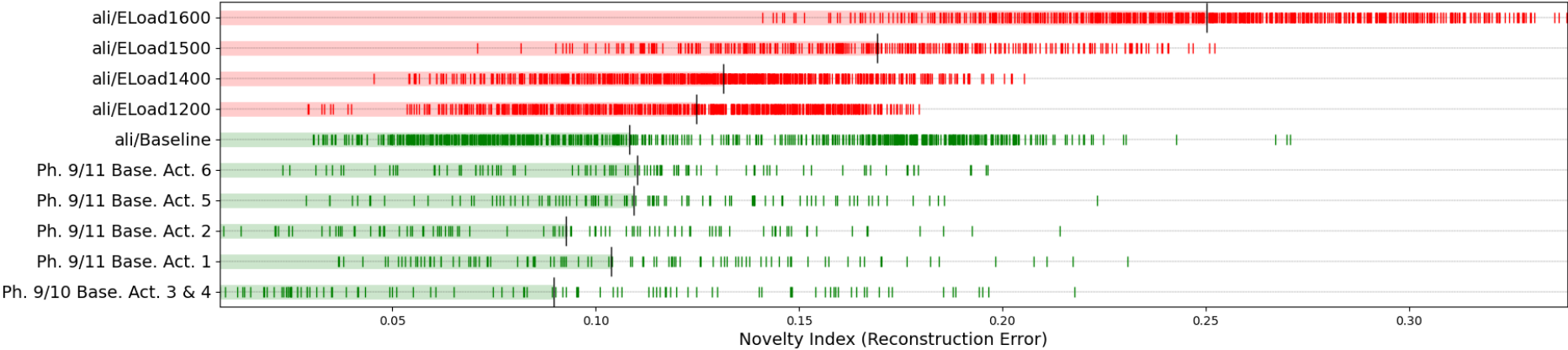
Multi-Actuator Data | Bottleneck of 11

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 11, 100 Epochs, 9 Fold Stratified



Multi-Actuator Data | Bottleneck of 12

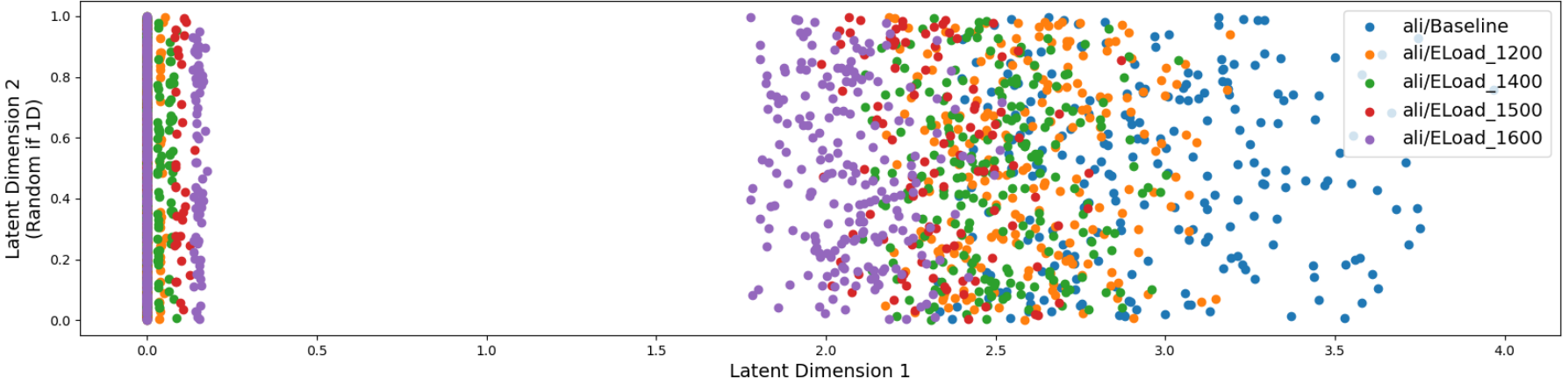
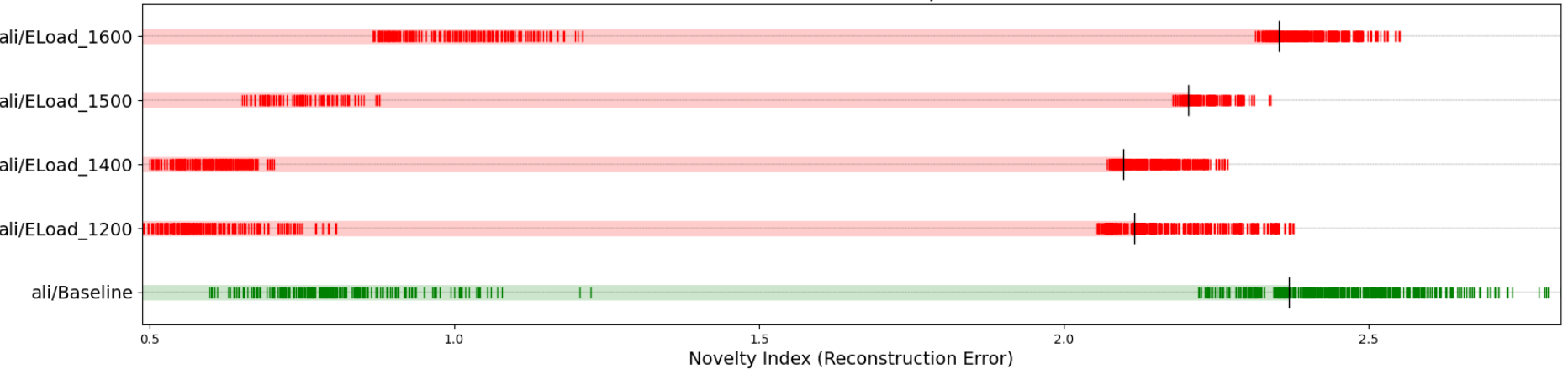
Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 12, 100 Epochs, 9 Fold Stratified



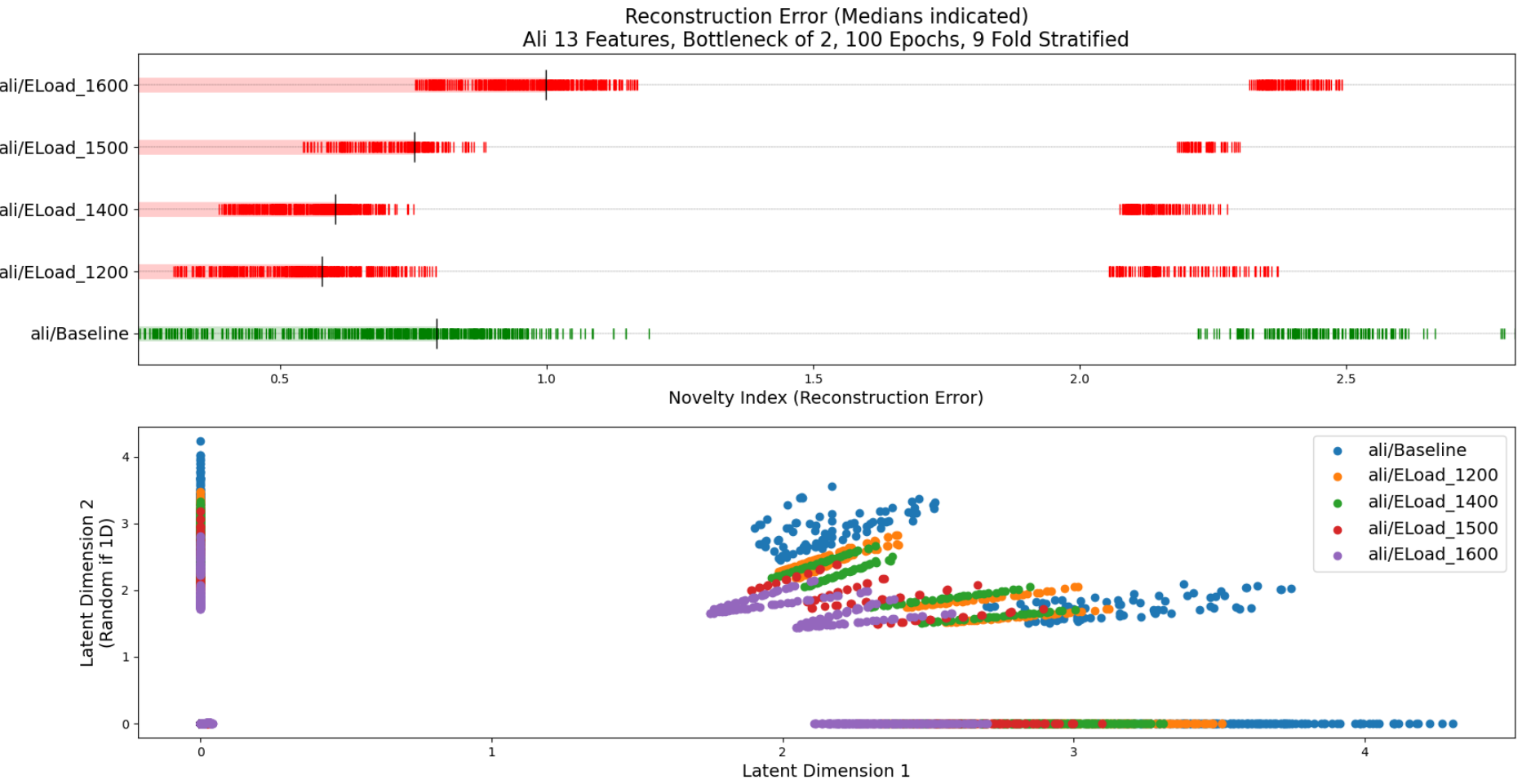
Single-Actuator Shallow Auto-encoder

Single-Actuator Data [Board 401] | Bottleneck of 1

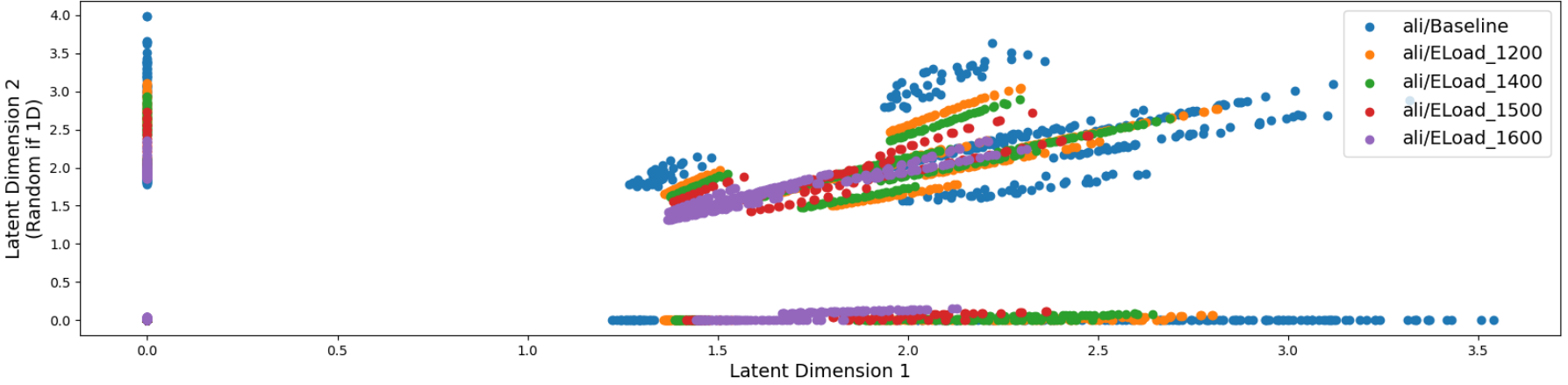
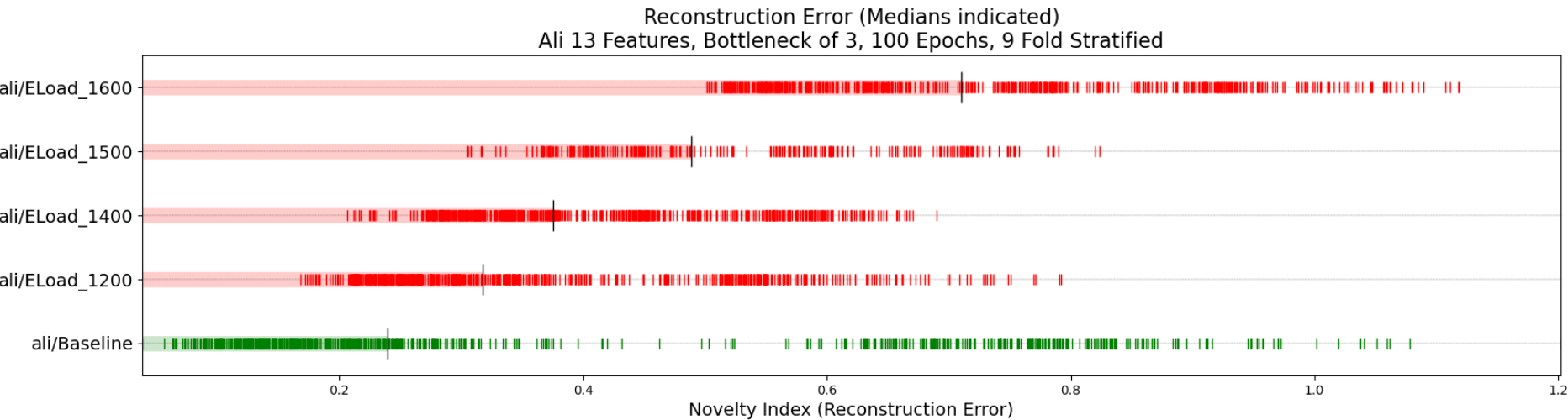
Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 1, 100 Epochs, 9 Fold Stratified



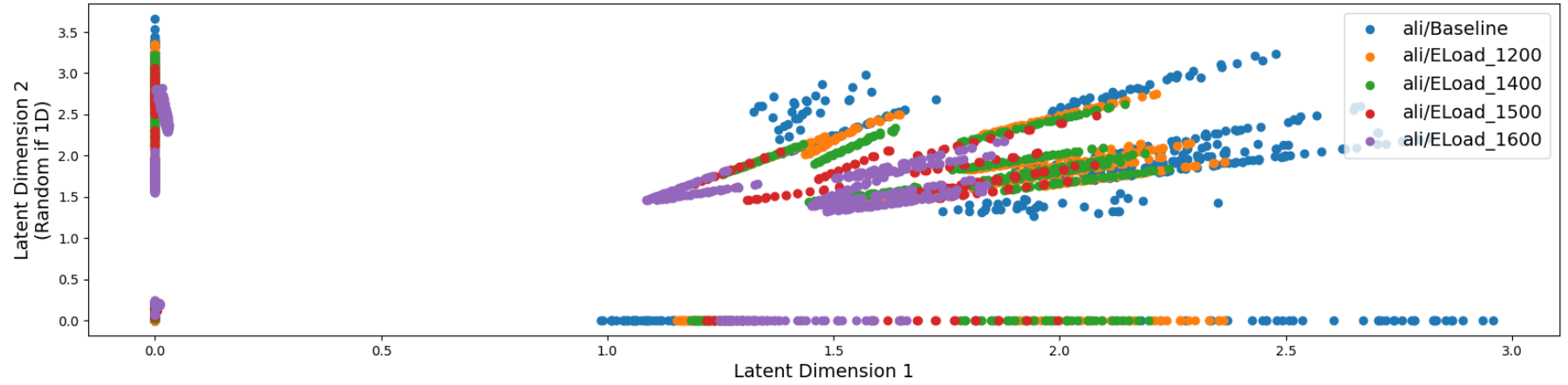
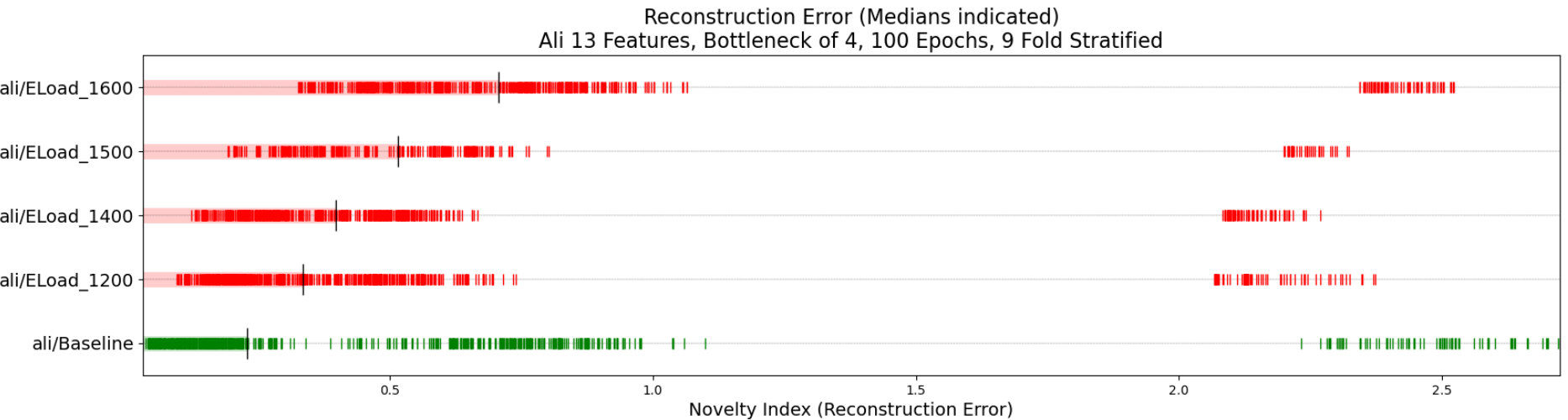
Single-Actuator Data [Board 401] | Bottleneck of 2



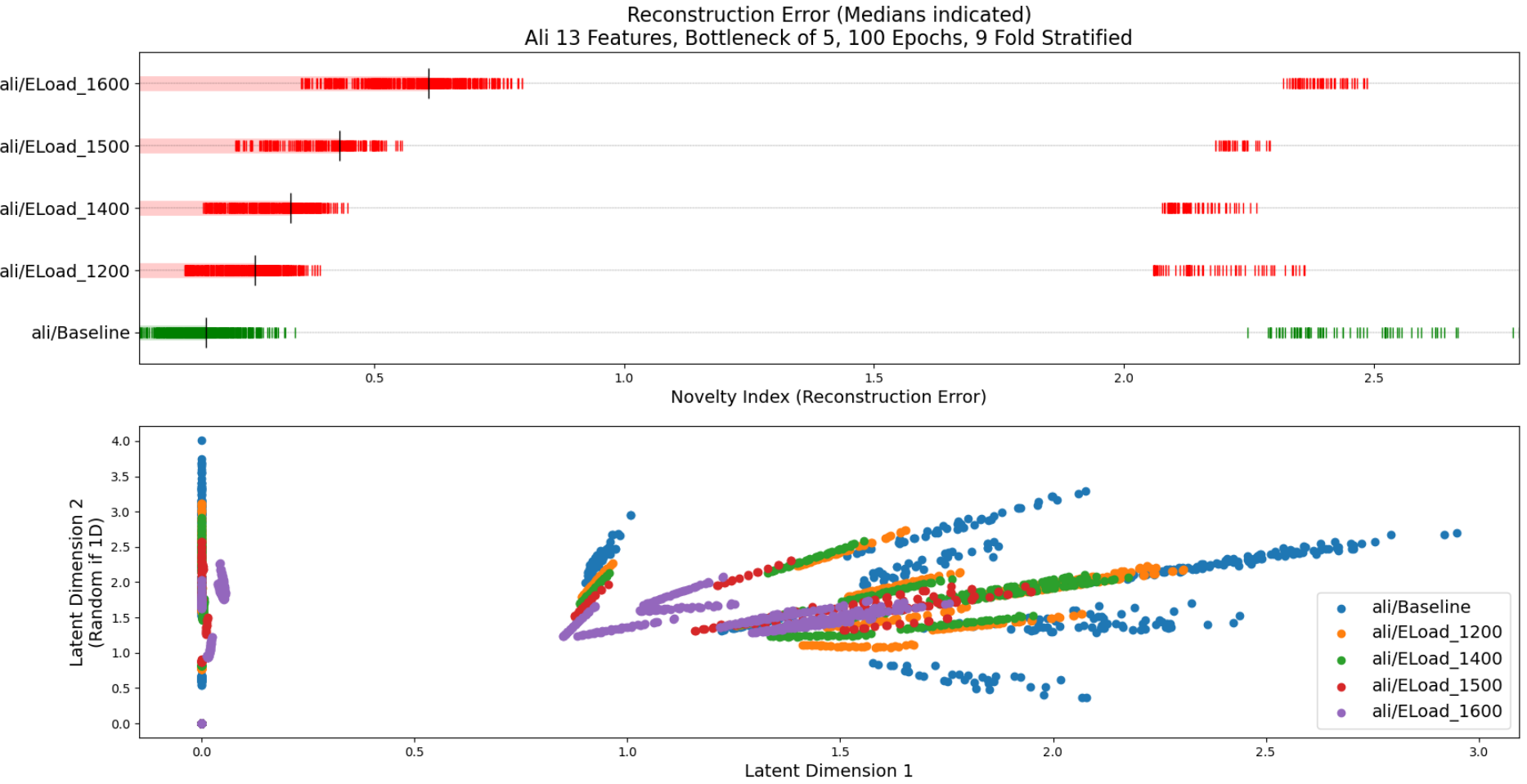
Single-Actuator Data [Board 401] | Bottleneck of 3



Single-Actuator Data [Board 401] | Bottleneck of 4

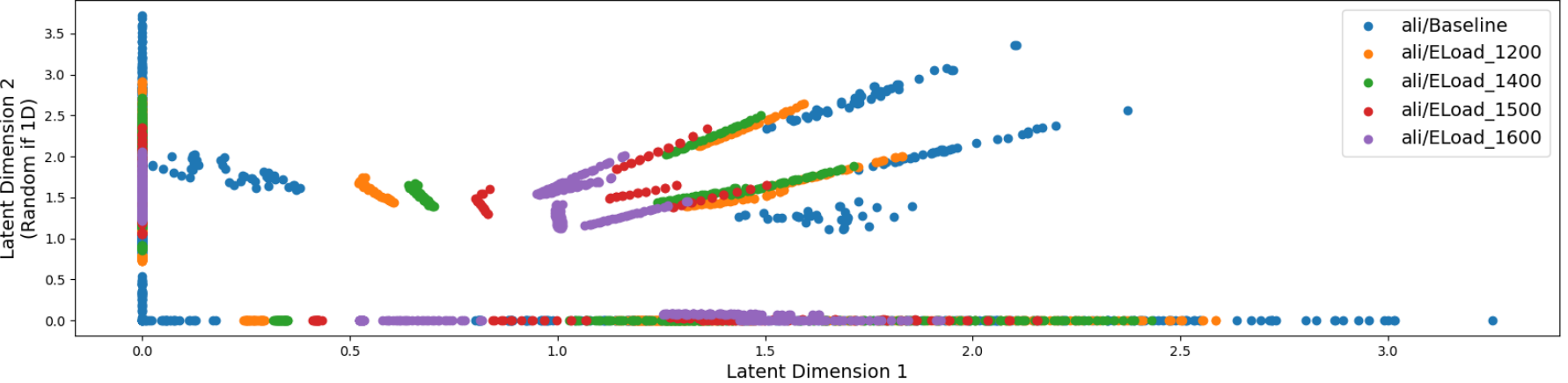
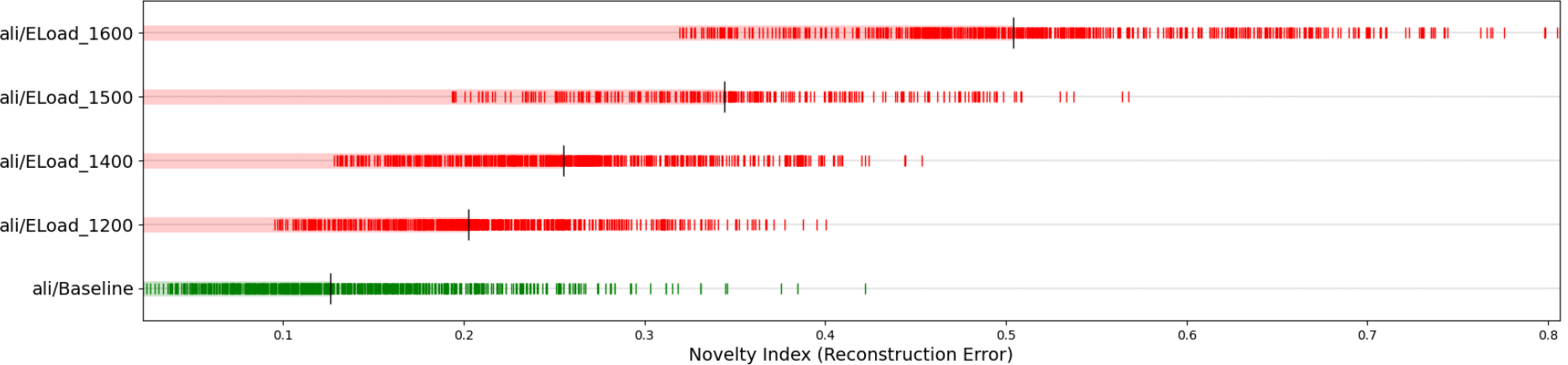


Single-Actuator Data [Board 401] | Bottleneck of 5



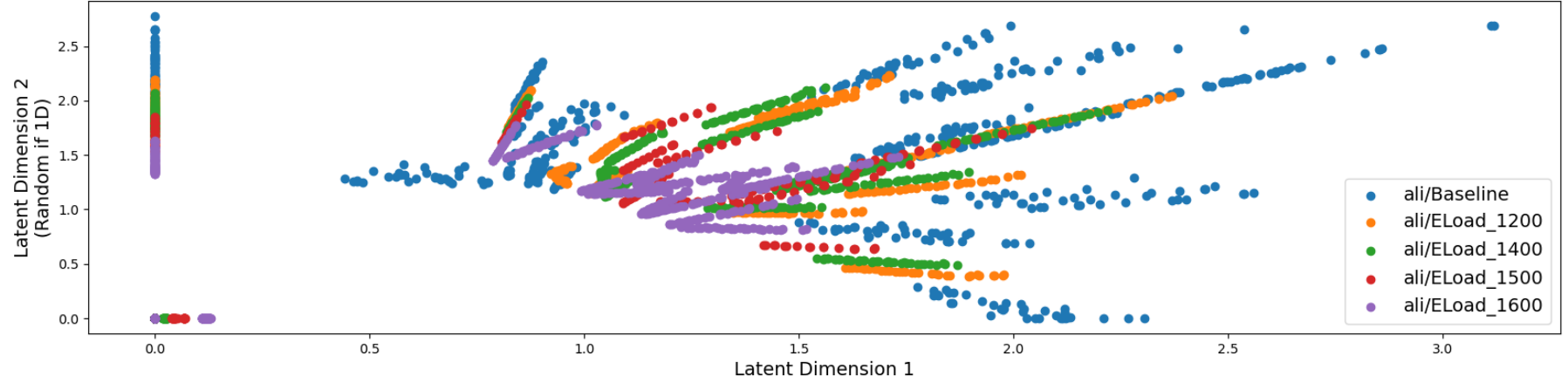
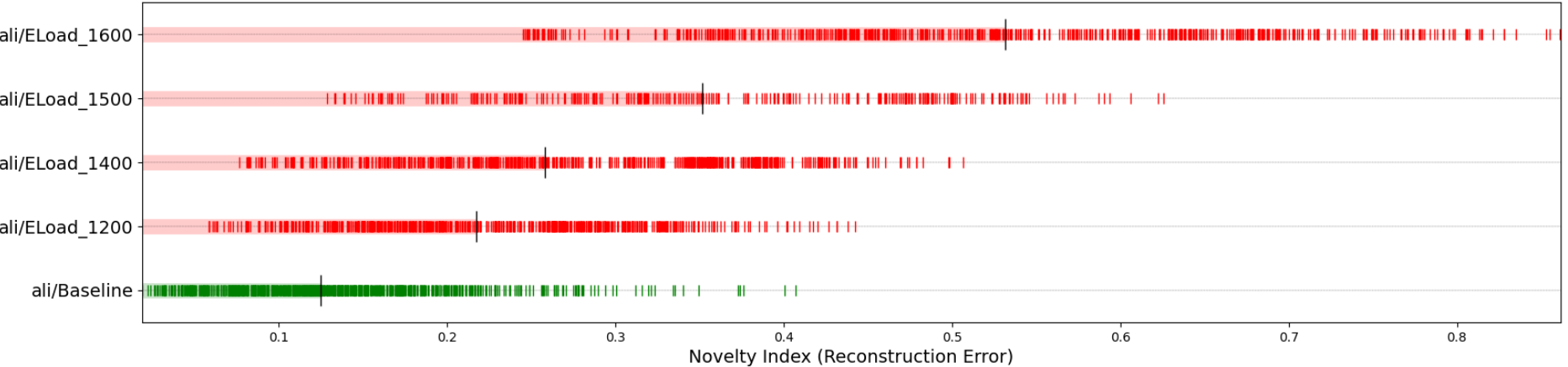
Single-Actuator Data [Board 401] | Bottleneck of 6

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 6, 100 Epochs, 9 Fold Stratified



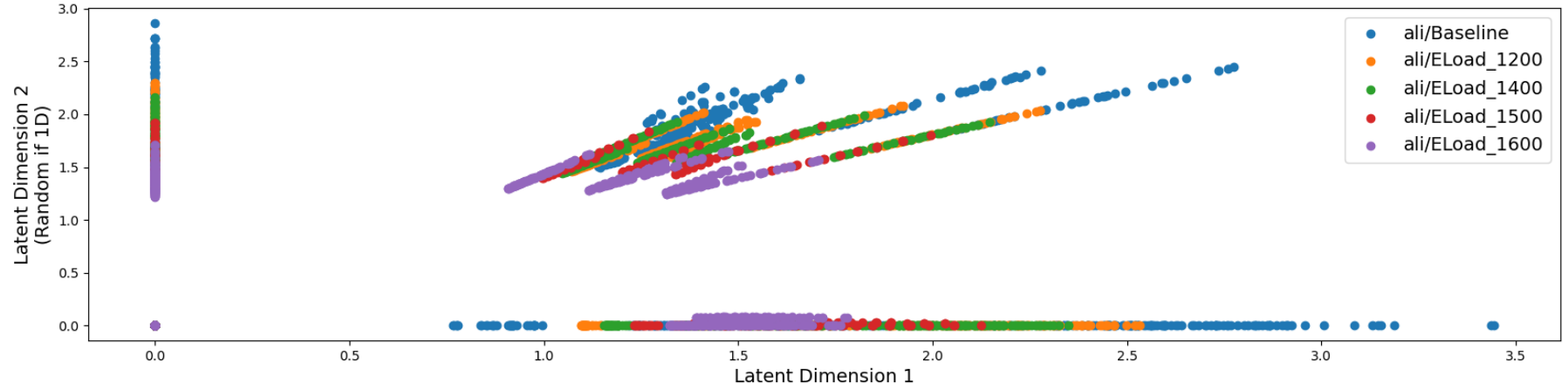
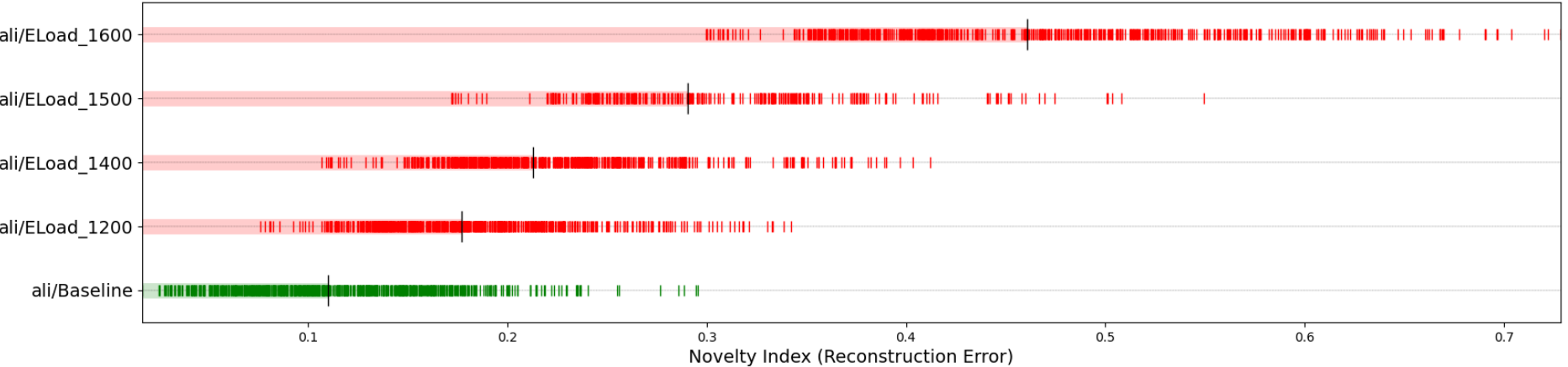
Single-Actuator Data [Board 401] | Bottleneck of 7

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 7, 100 Epochs, 9 Fold Stratified

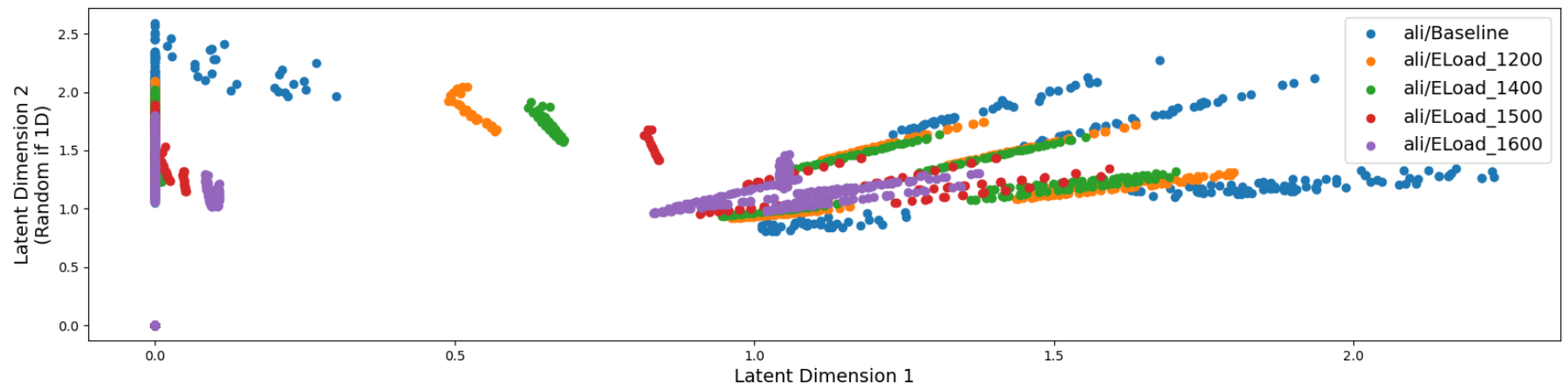
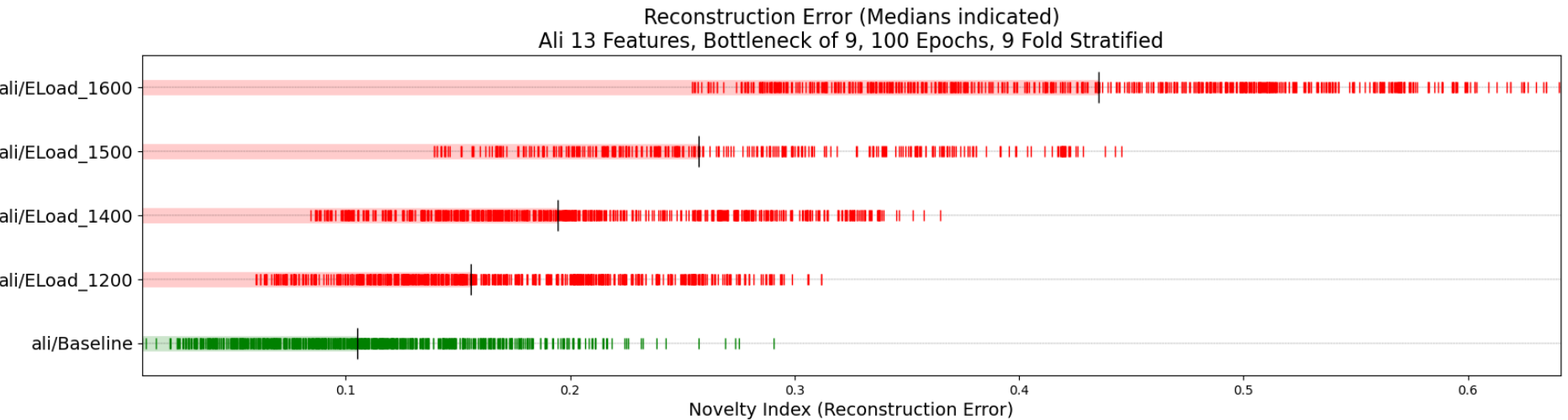


Single-Actuator Data [Board 401] | Bottleneck of 8

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 8, 100 Epochs, 9 Fold Stratified

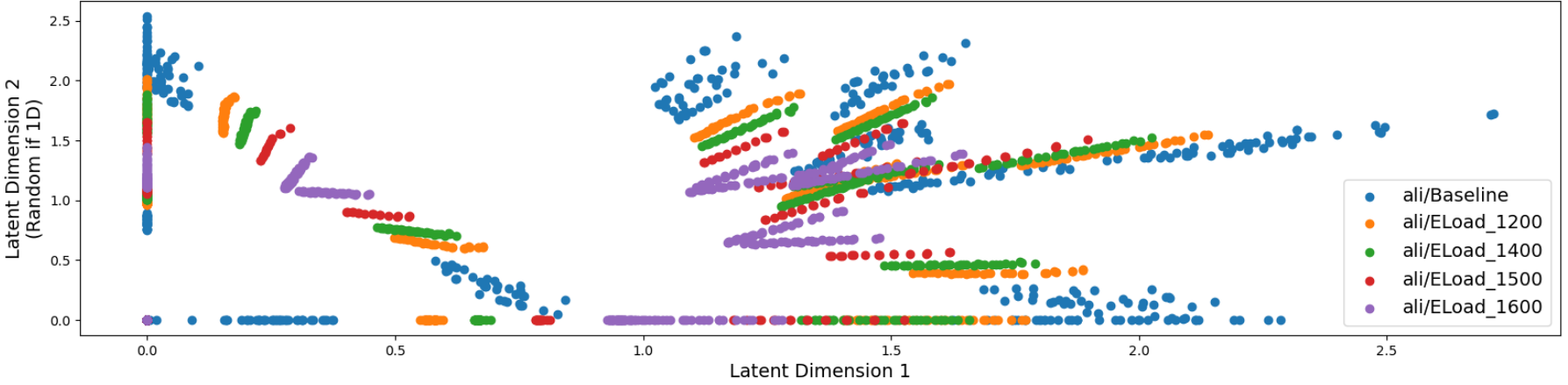
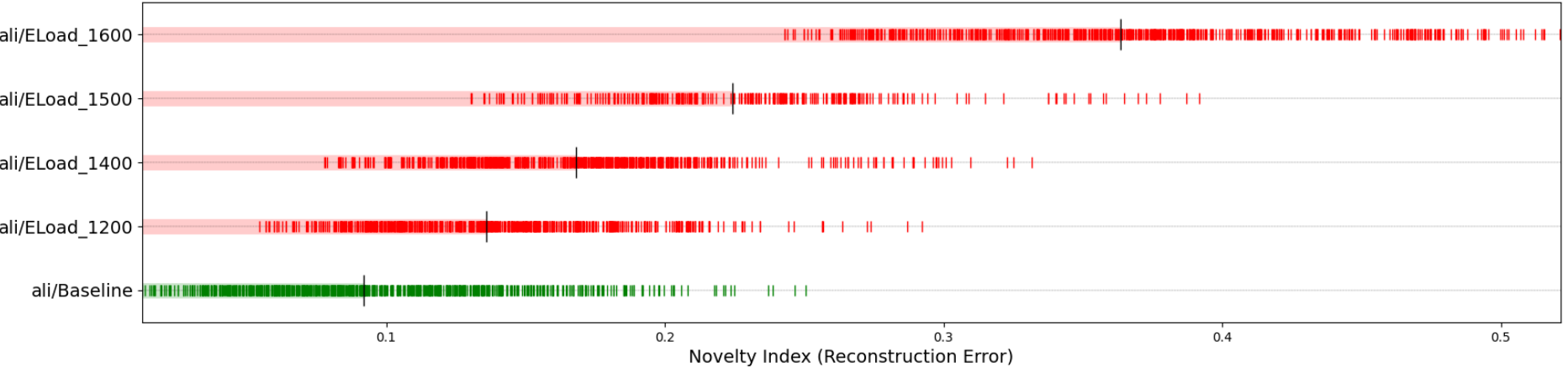


Single-Actuator Data [Board 401] | Bottleneck of 9



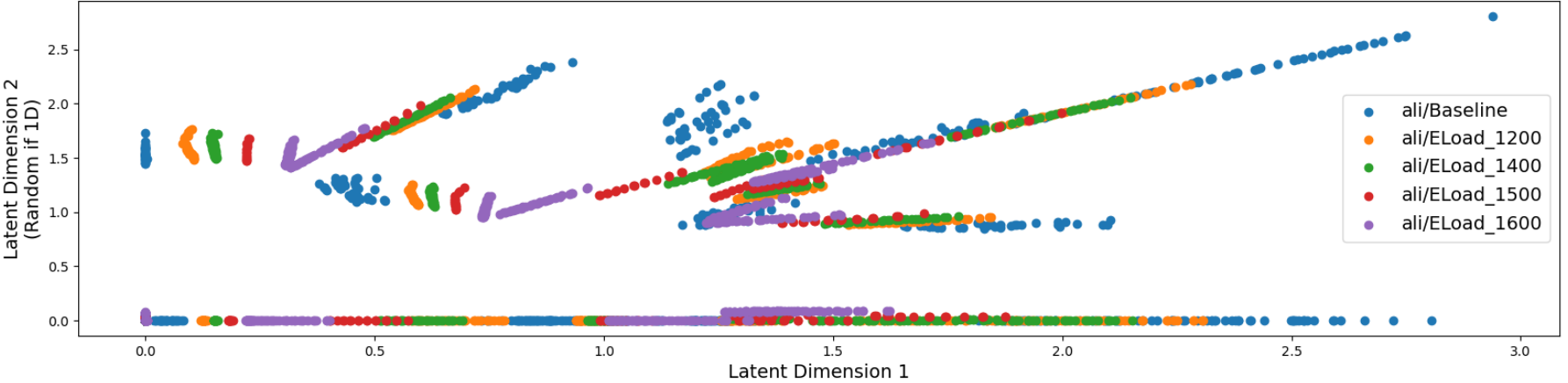
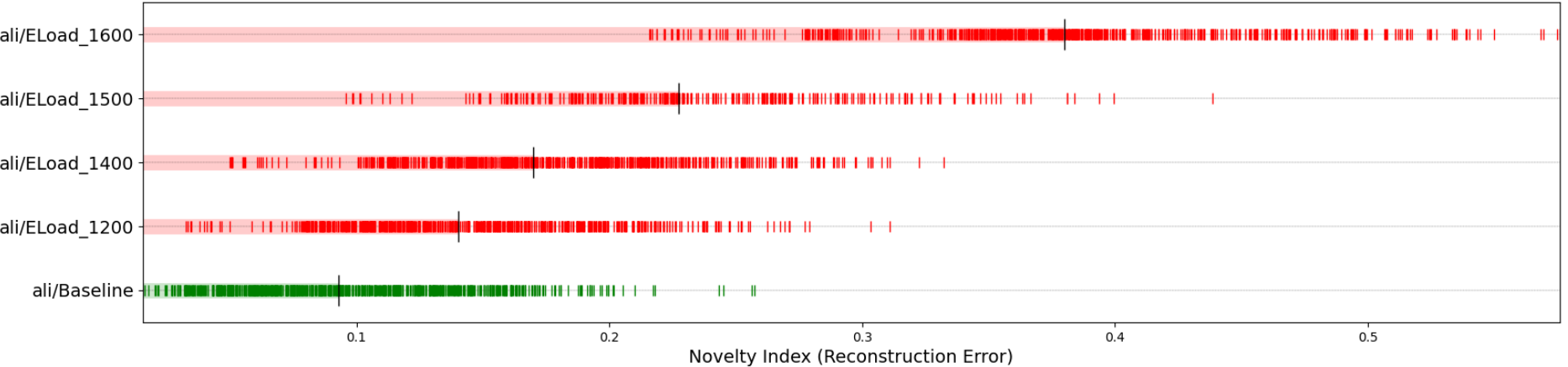
Single-Actuator Data [Board 401] | Bottleneck of 10

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 10, 100 Epochs, 9 Fold Stratified

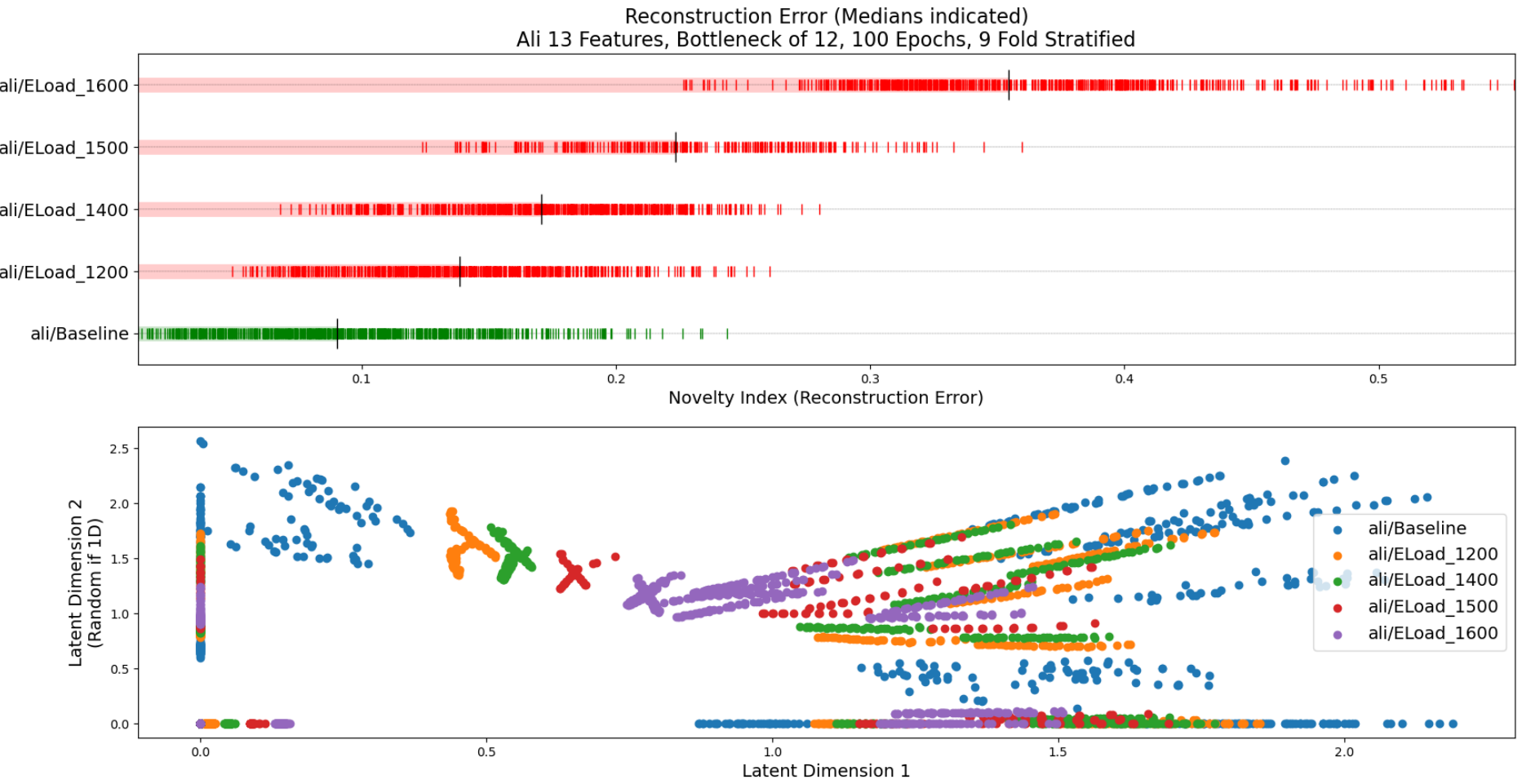


Single-Actuator Data [Board 401] | Bottleneck of 11

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 11, 100 Epochs, 9 Fold Stratified



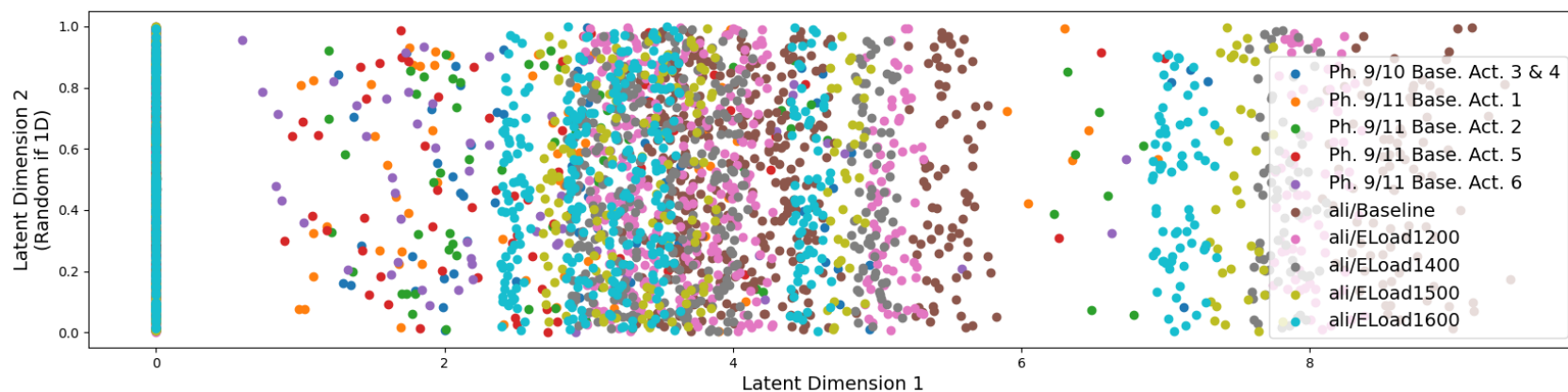
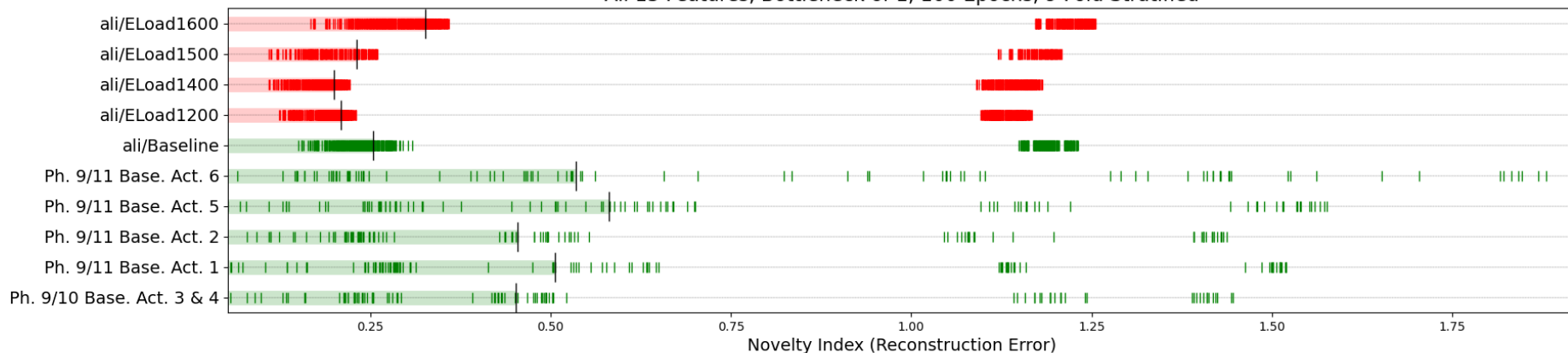
Single-Actuator Data [Board 401] | Bottleneck of 12



Multi-Actuator Deep Auto-encoder

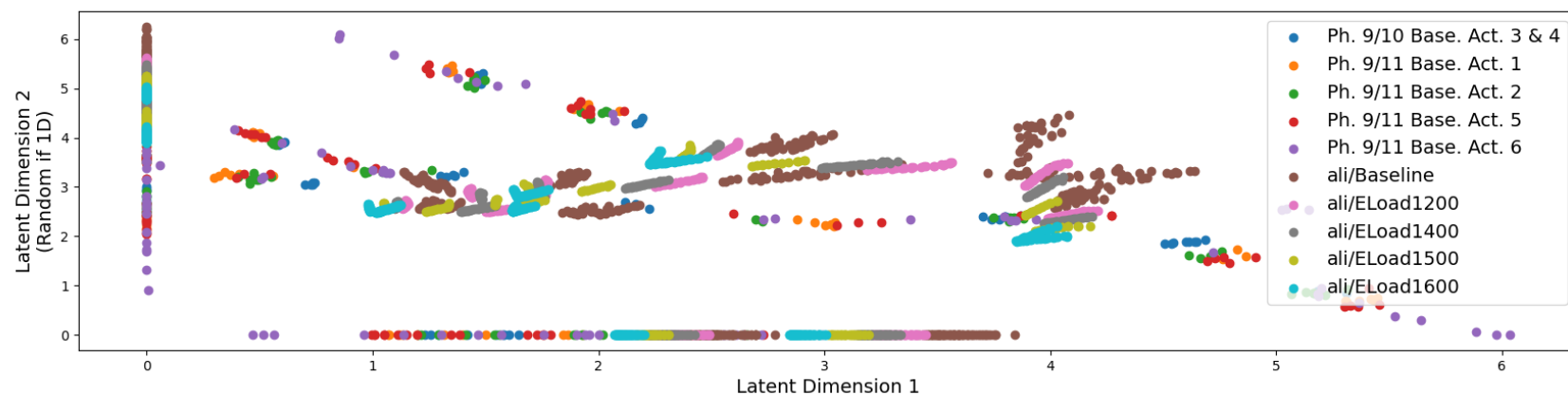
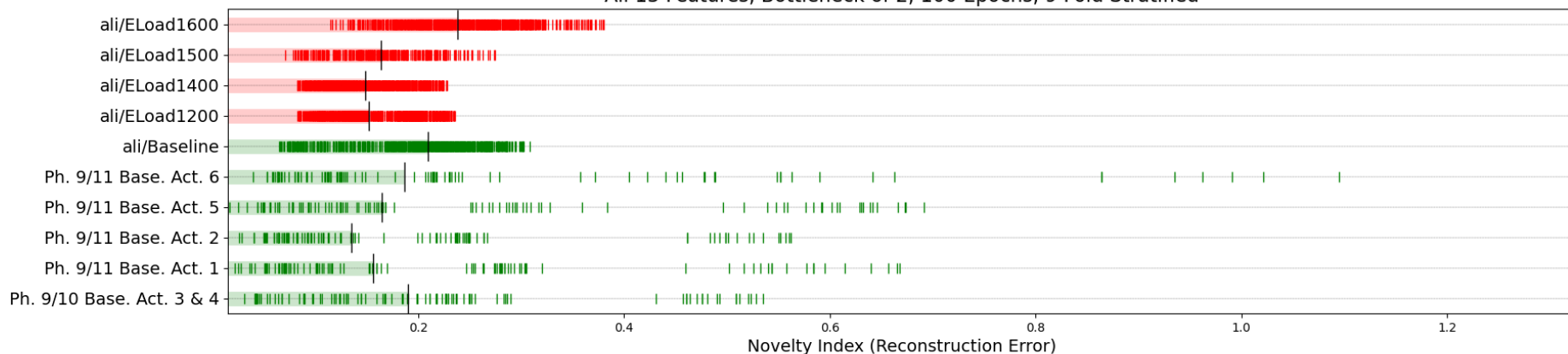
Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 1

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 1, 100 Epochs, 9 Fold Stratified



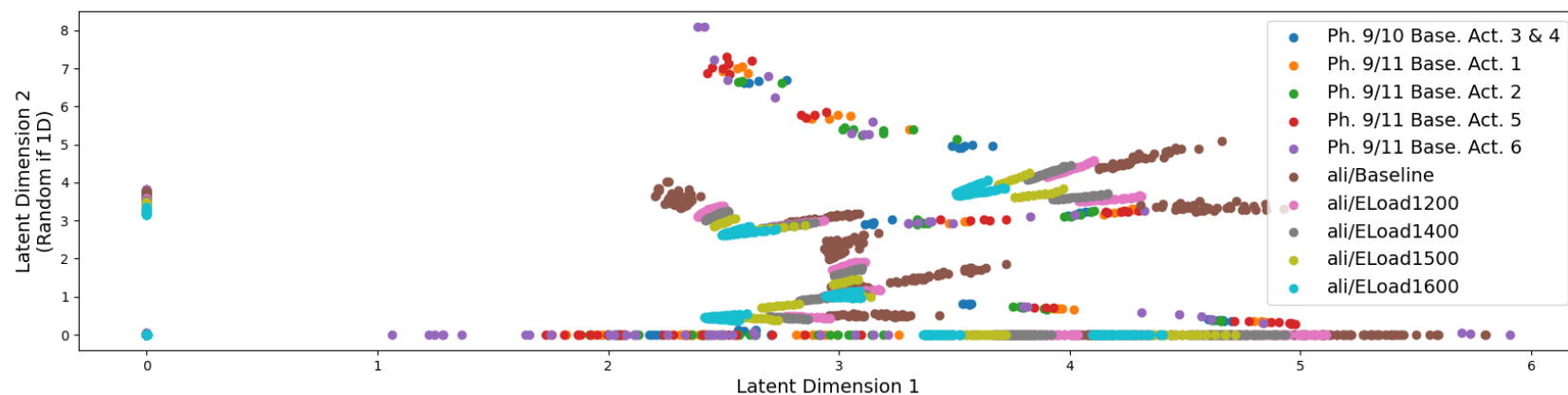
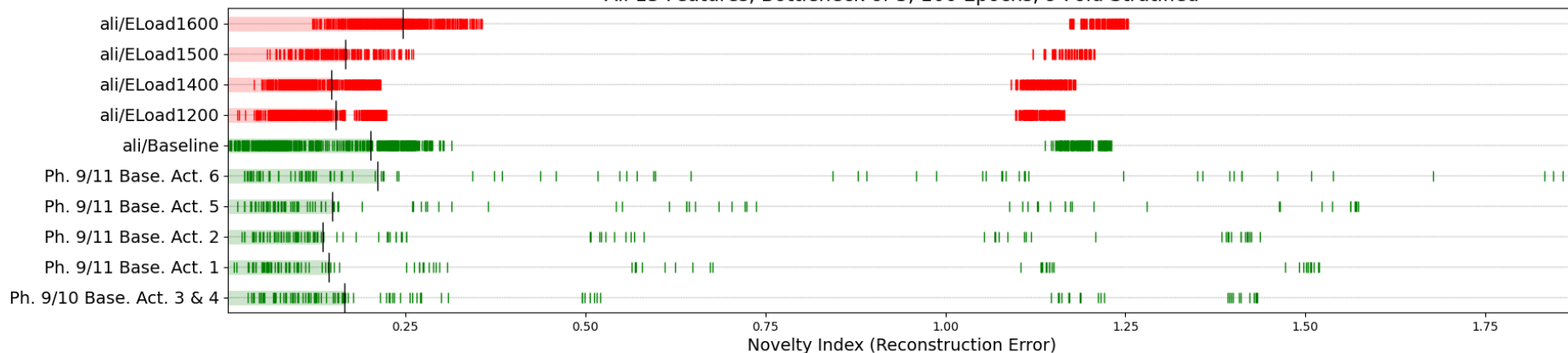
Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 2

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 2, 100 Epochs, 9 Fold Stratified

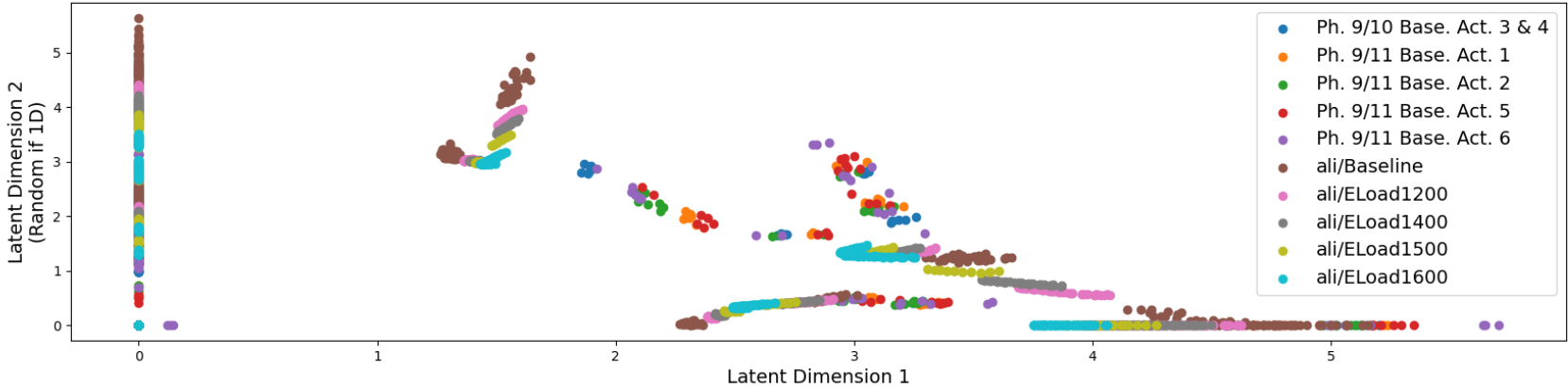
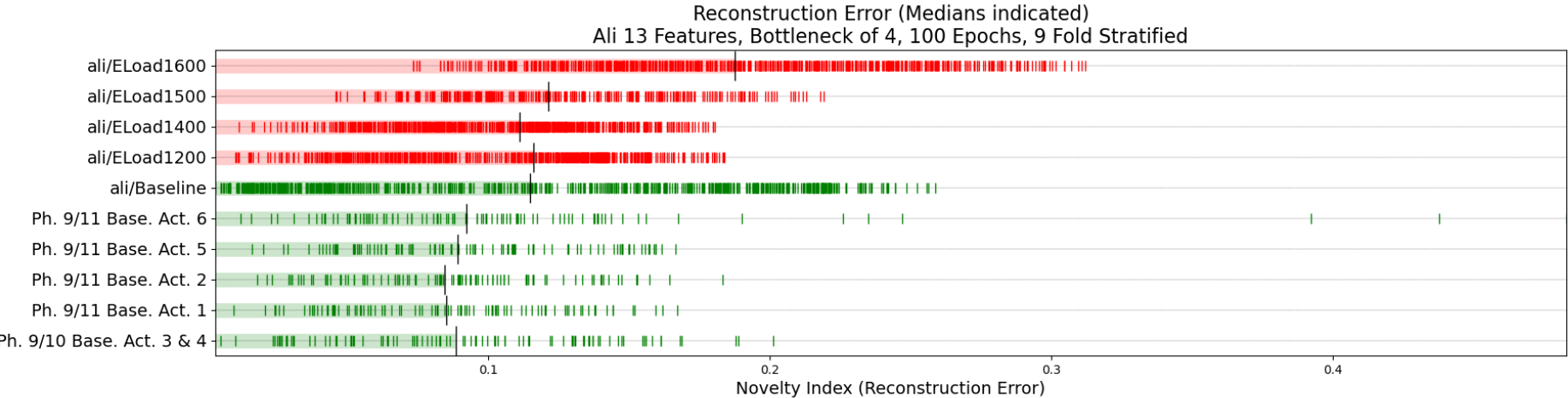


Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 3

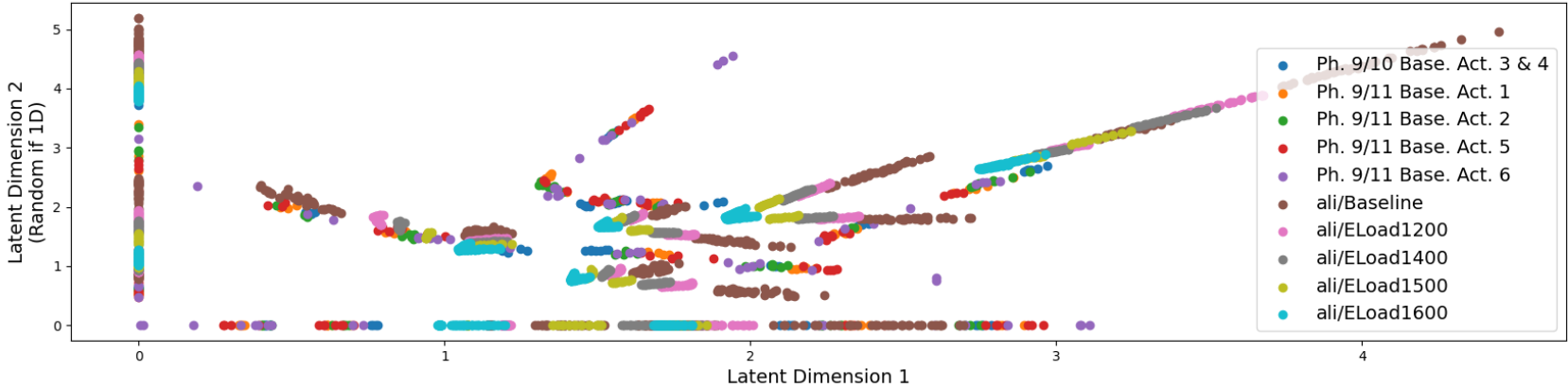
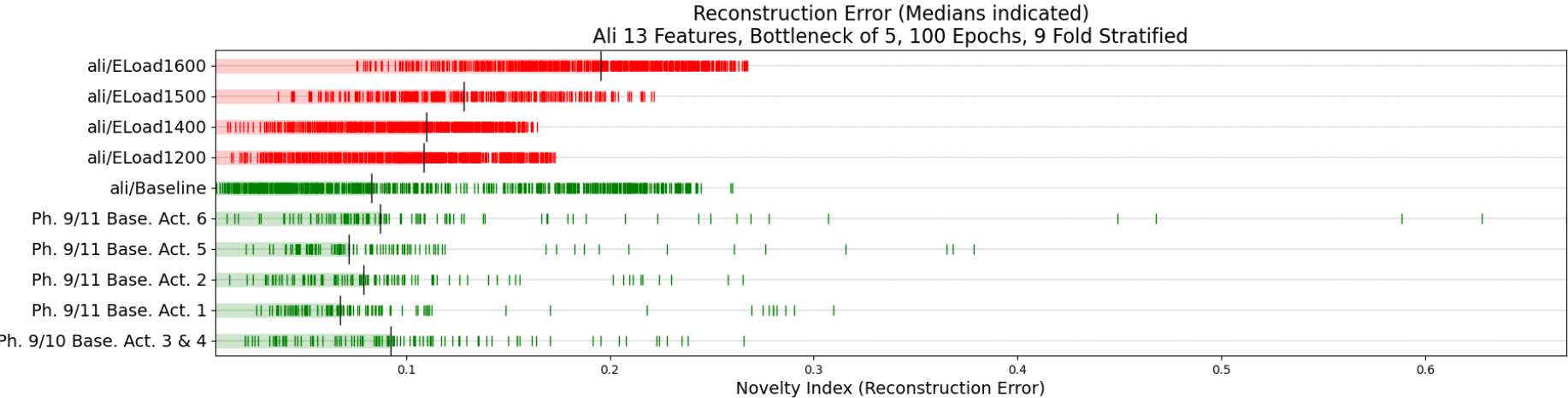
Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 3, 100 Epochs, 9 Fold Stratified



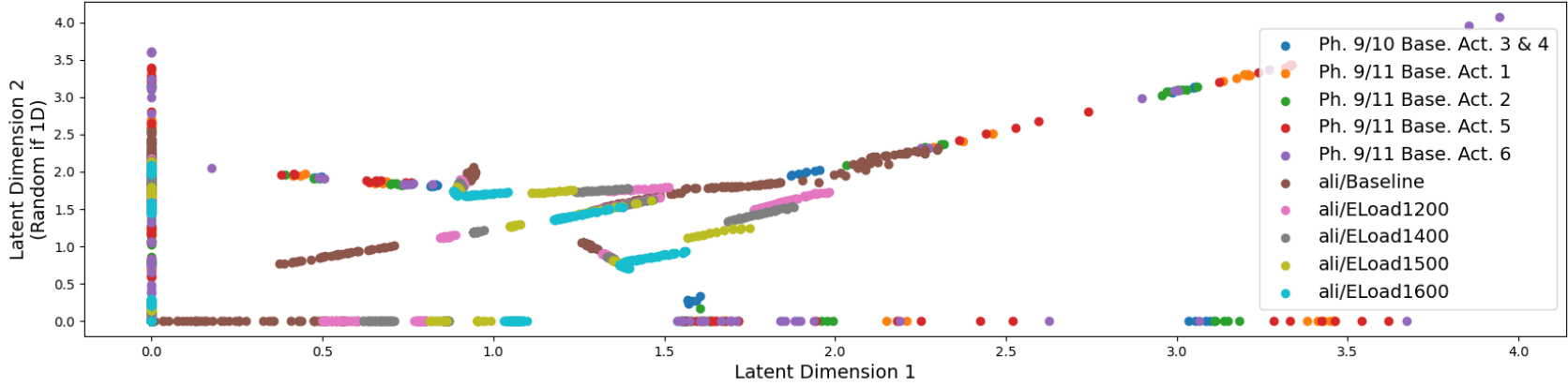
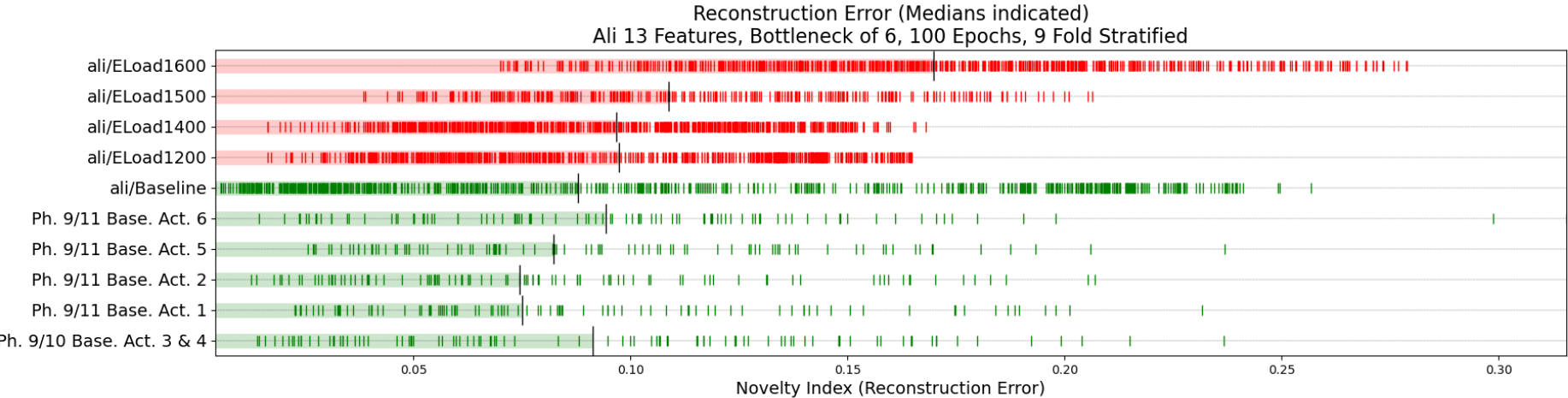
Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 4



Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 5

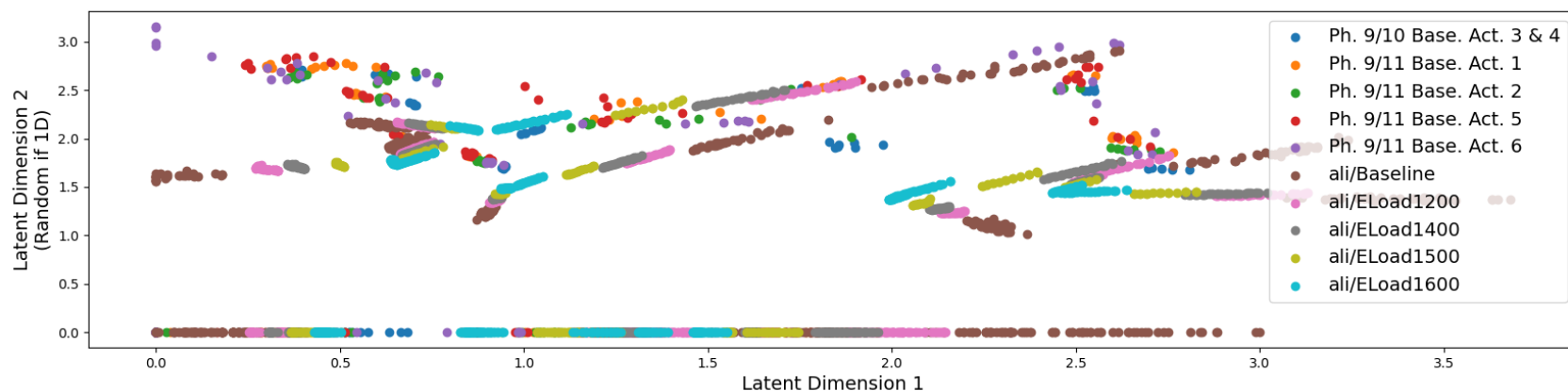
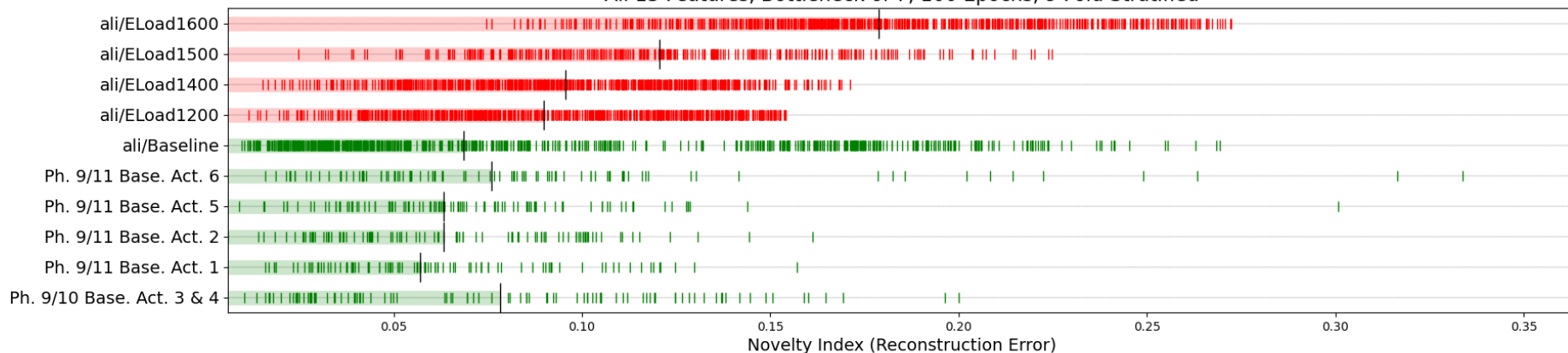


Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 6

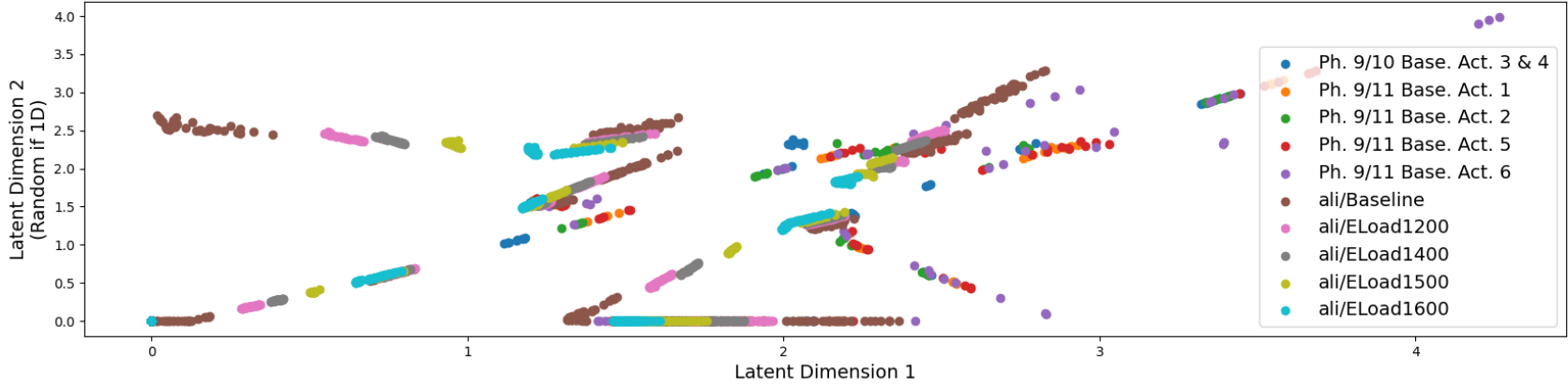
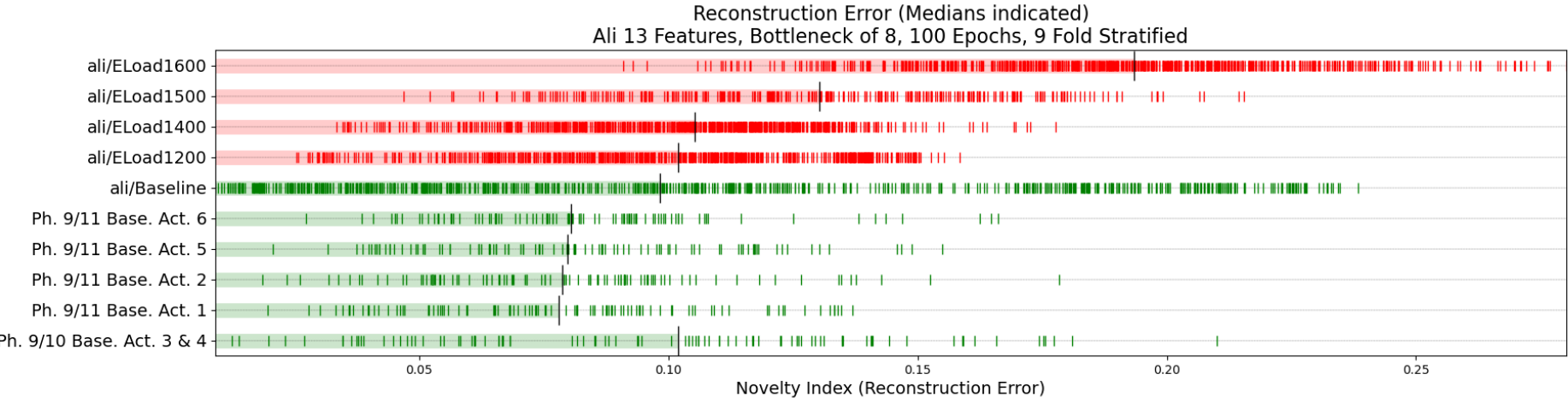


Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 7

Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 7, 100 Epochs, 9 Fold Stratified

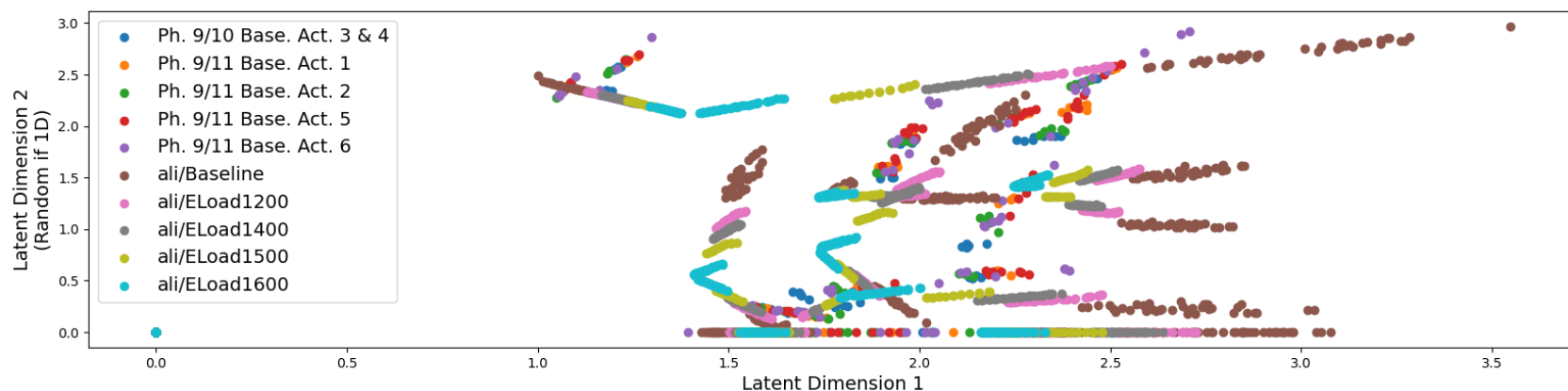
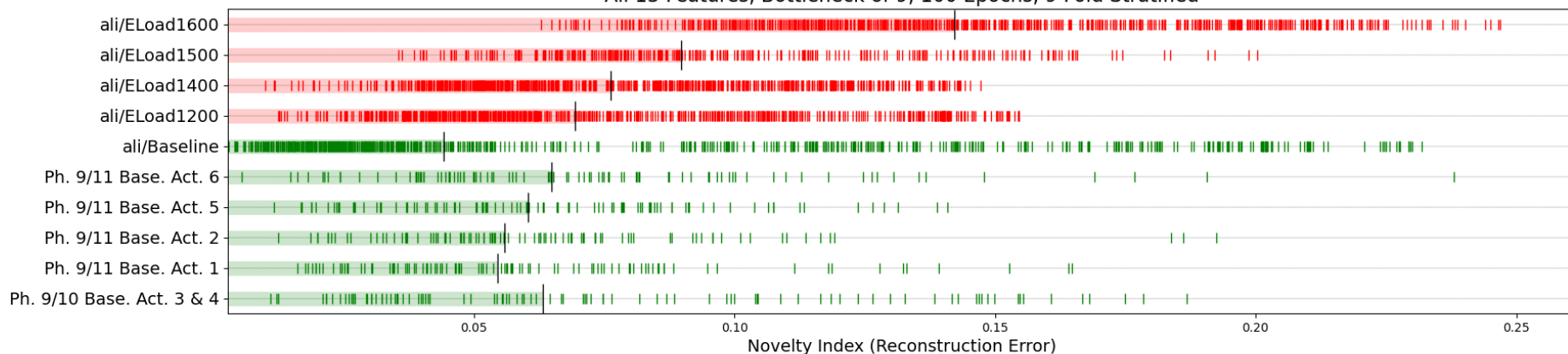


Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 8

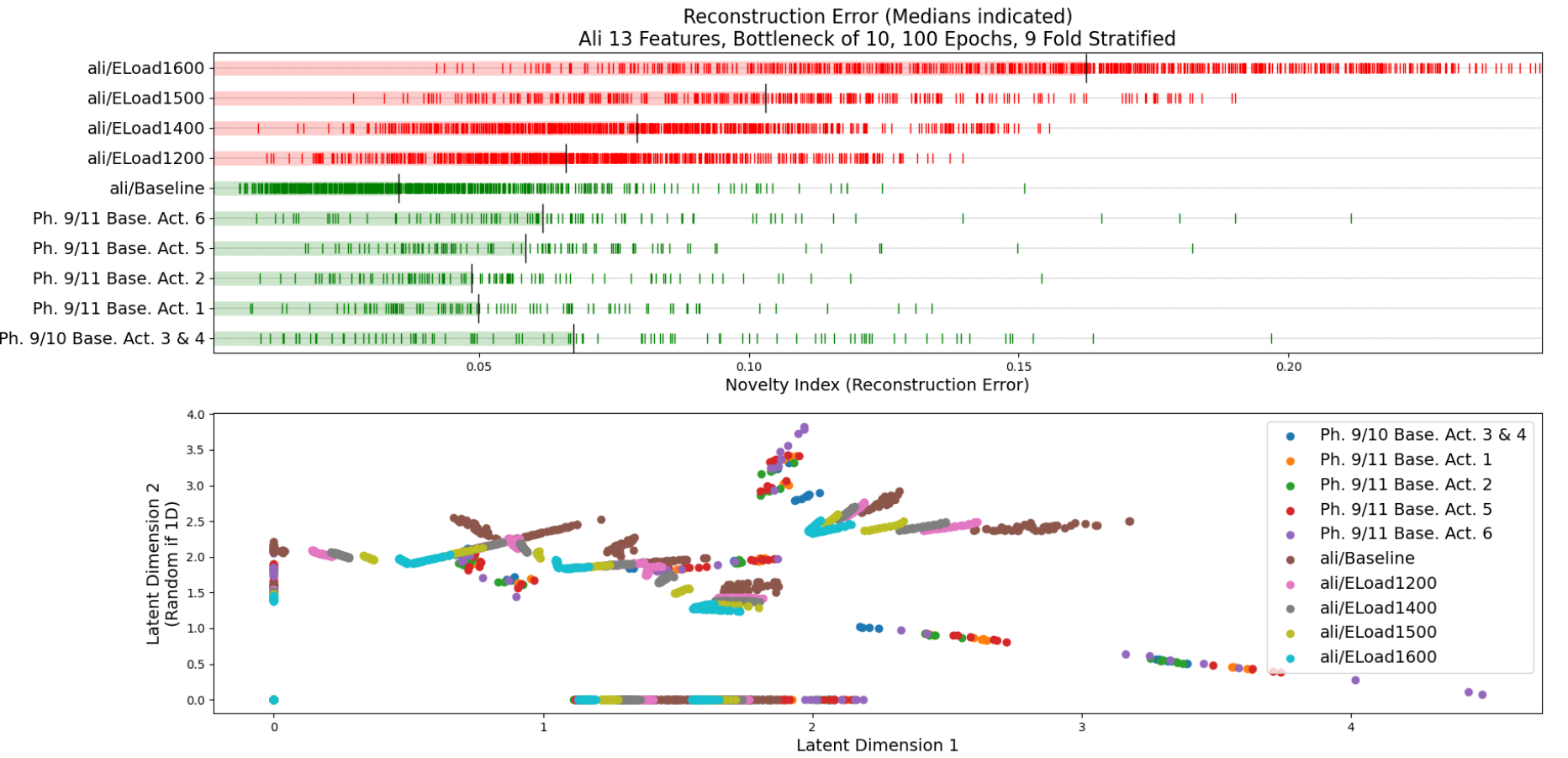


Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 9

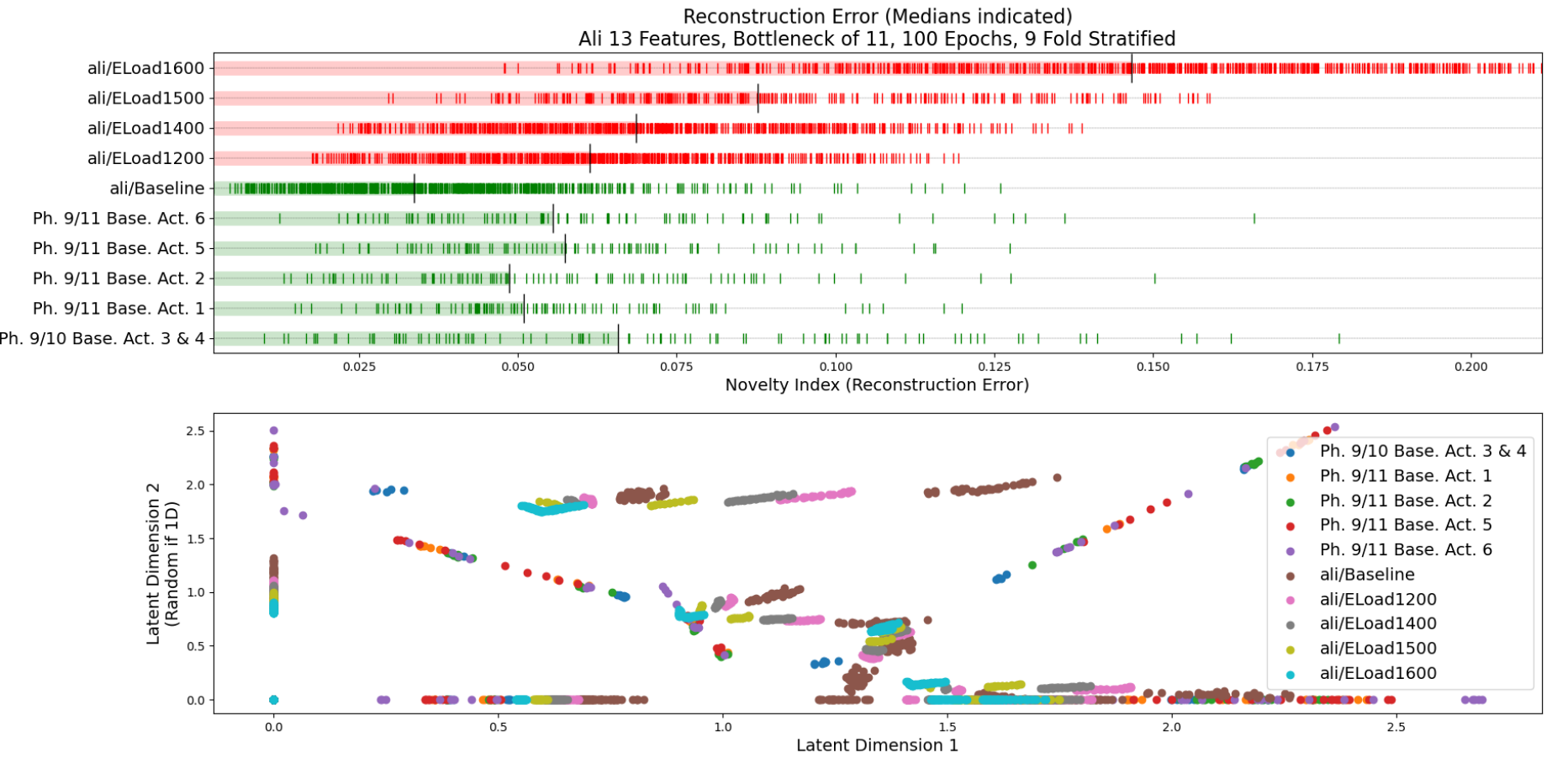
Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 9, 100 Epochs, 9 Fold Stratified



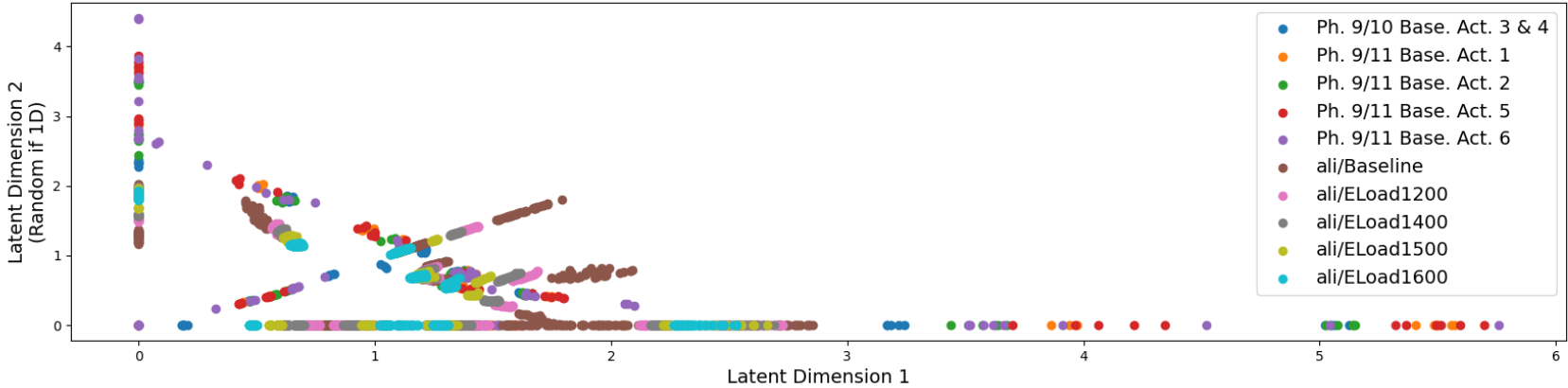
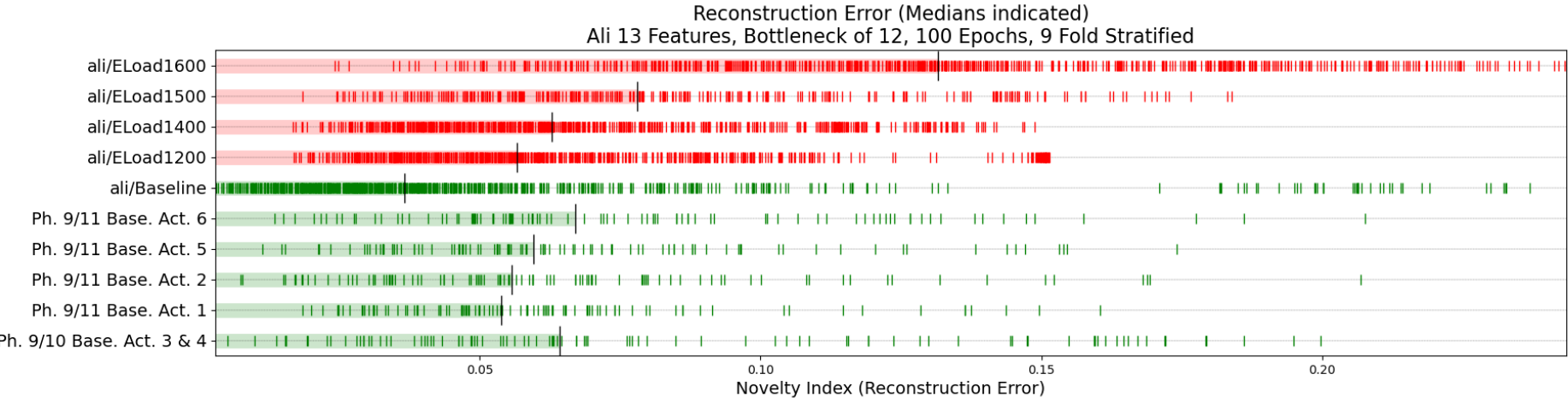
Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 10



Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 11

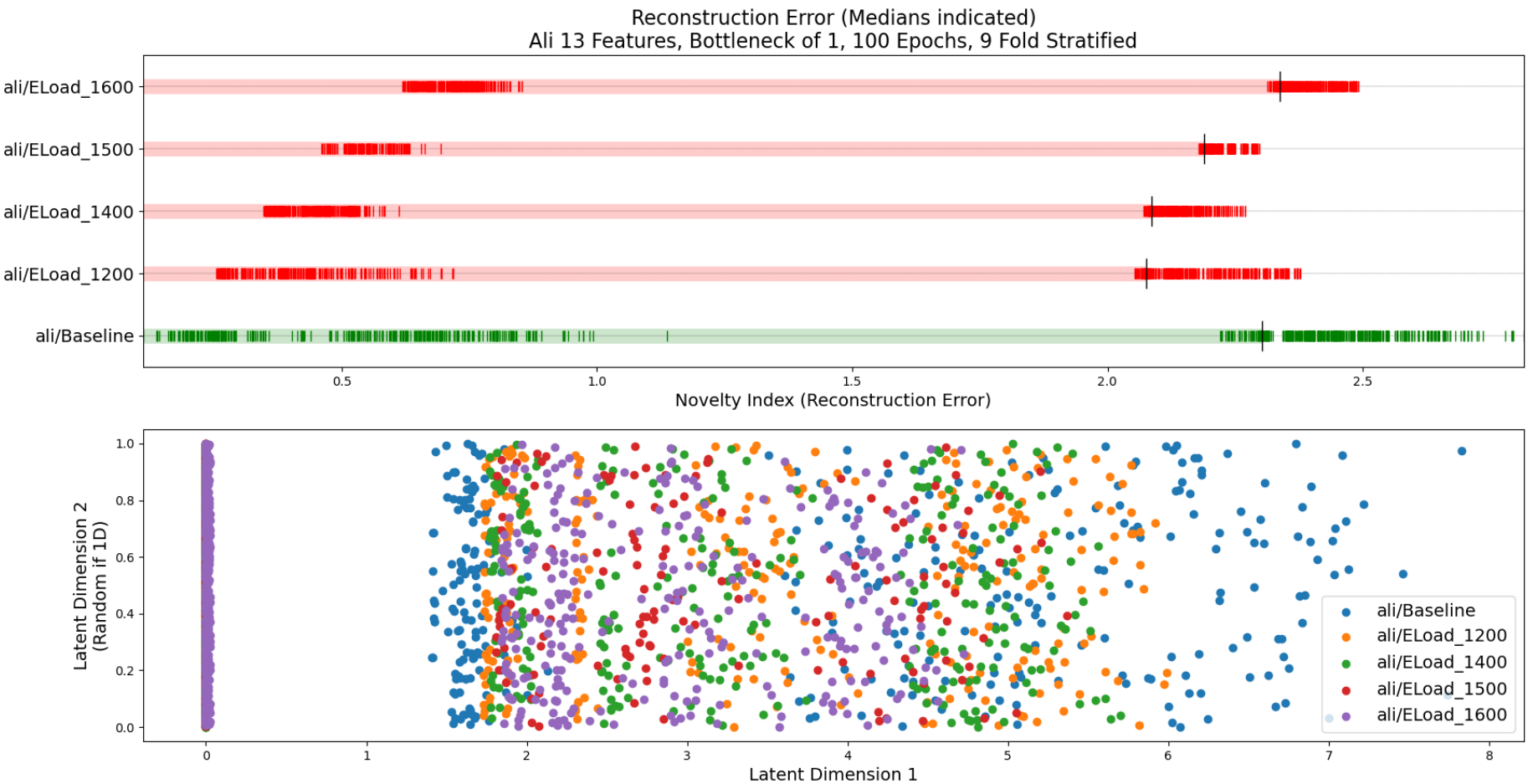


Multi-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 12

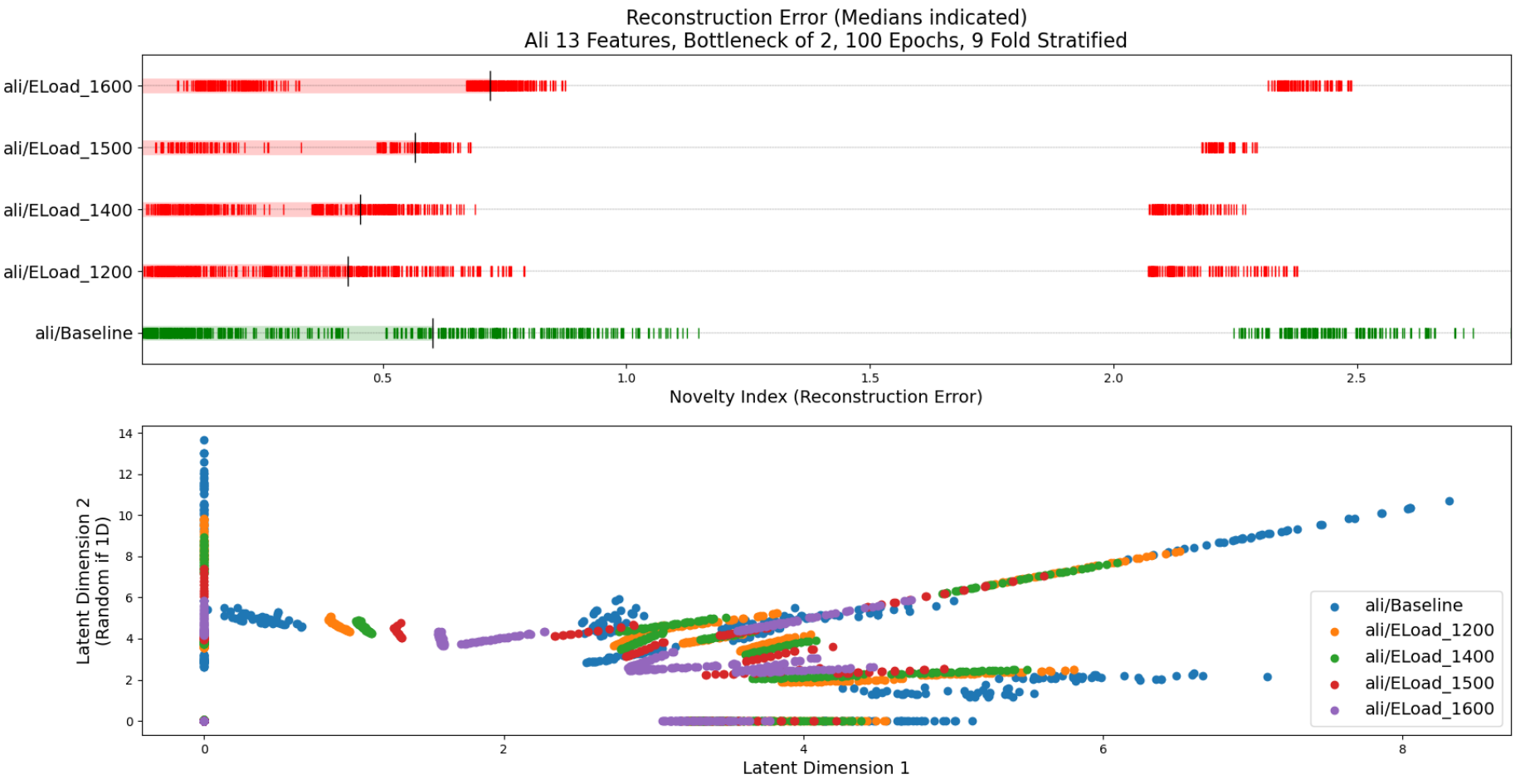


Single-Actuator Deep Auto-encoder

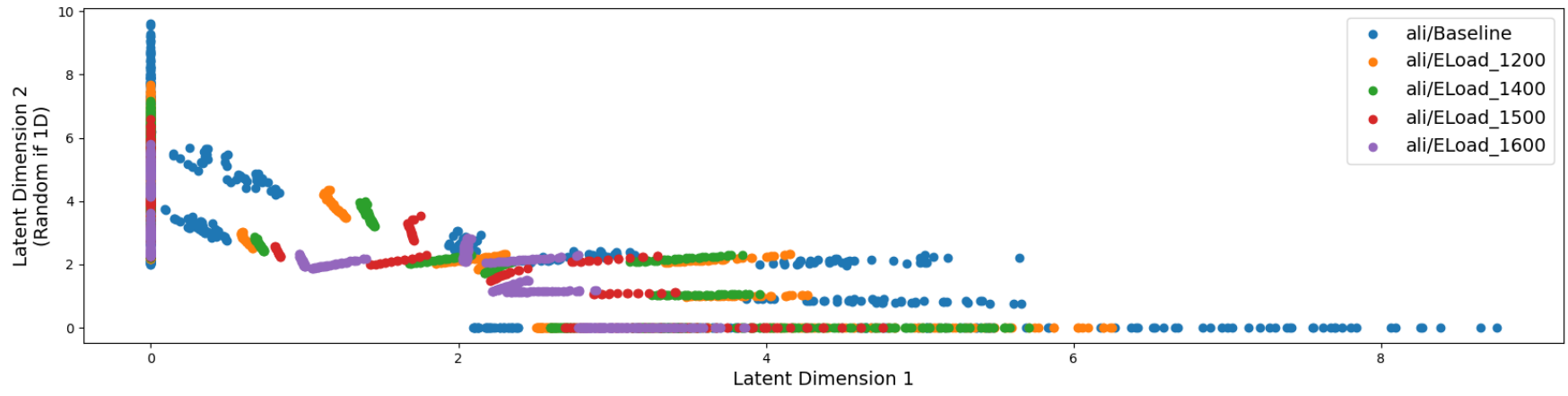
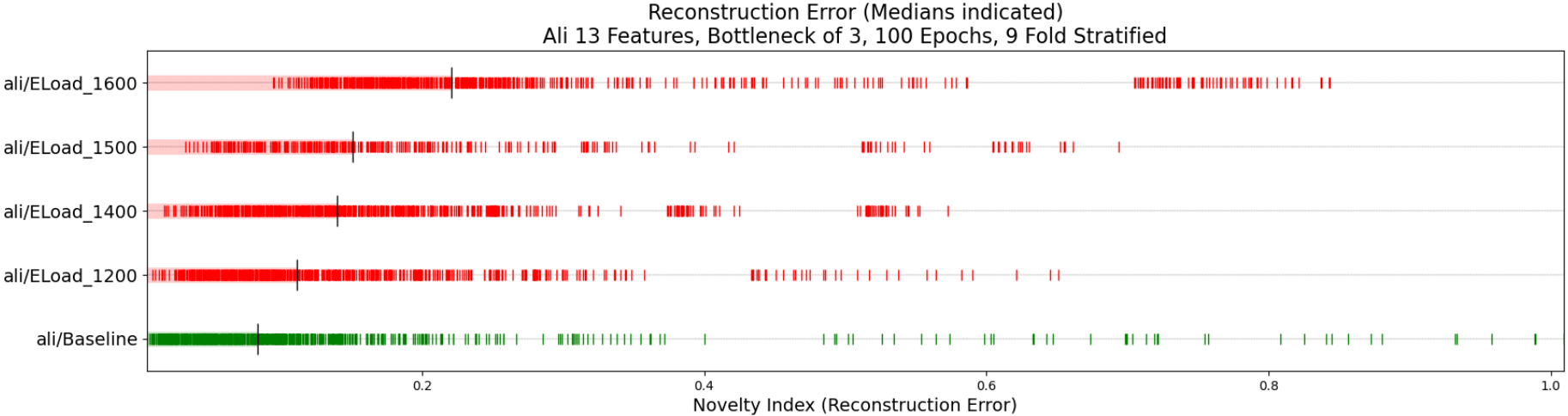
Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 1



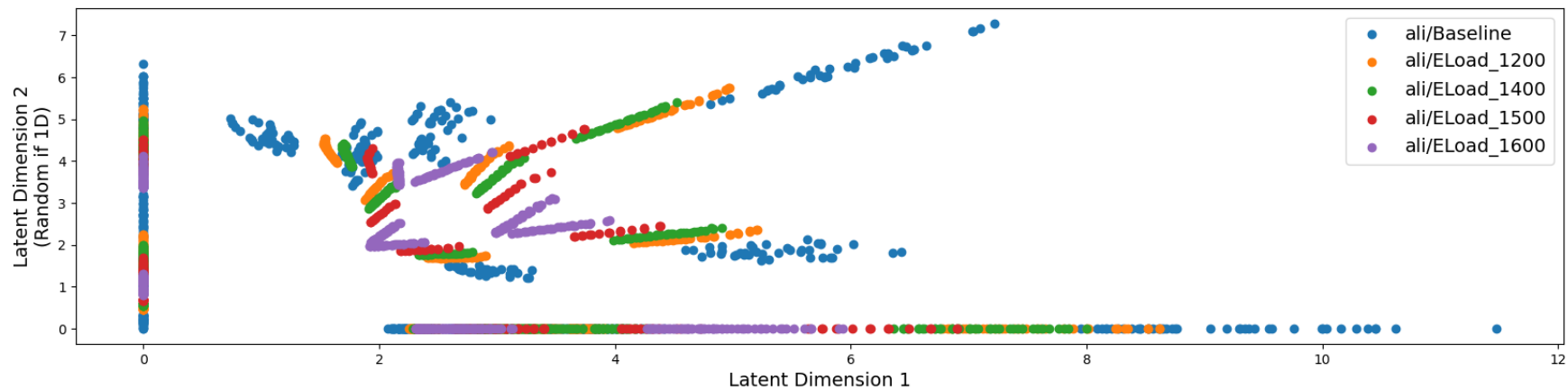
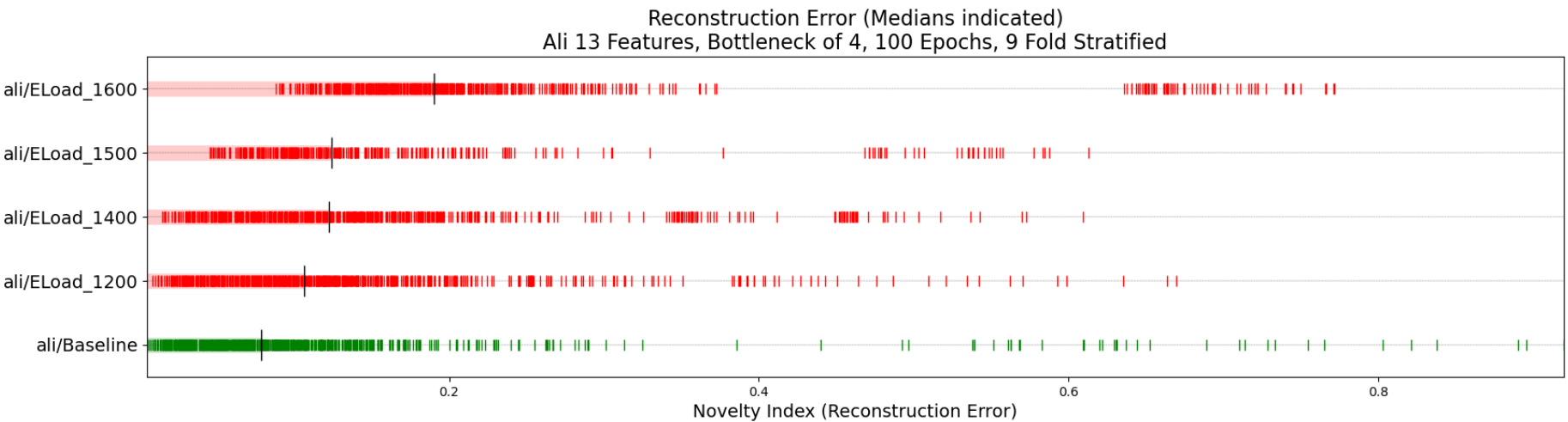
Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 2



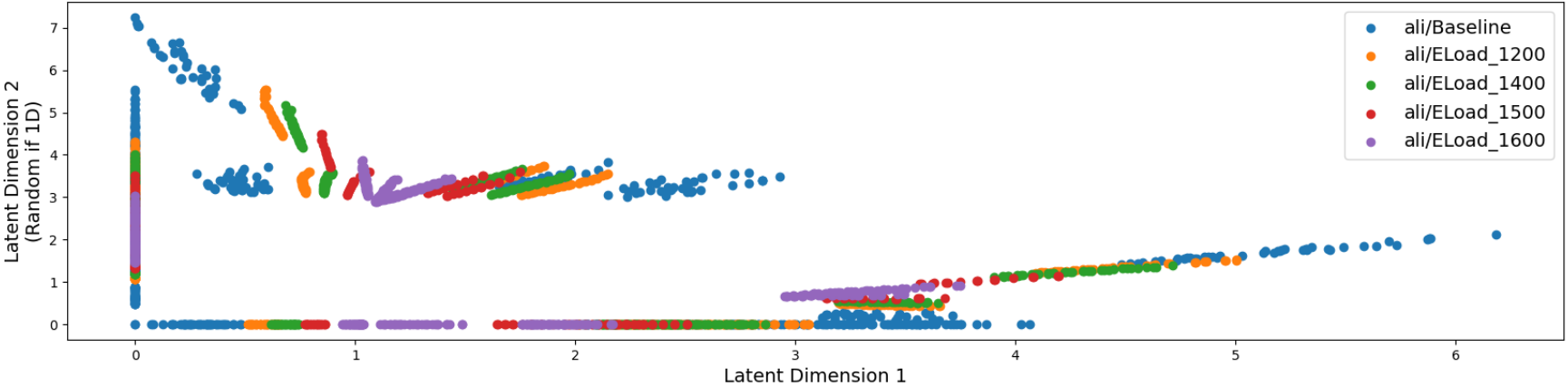
Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 3



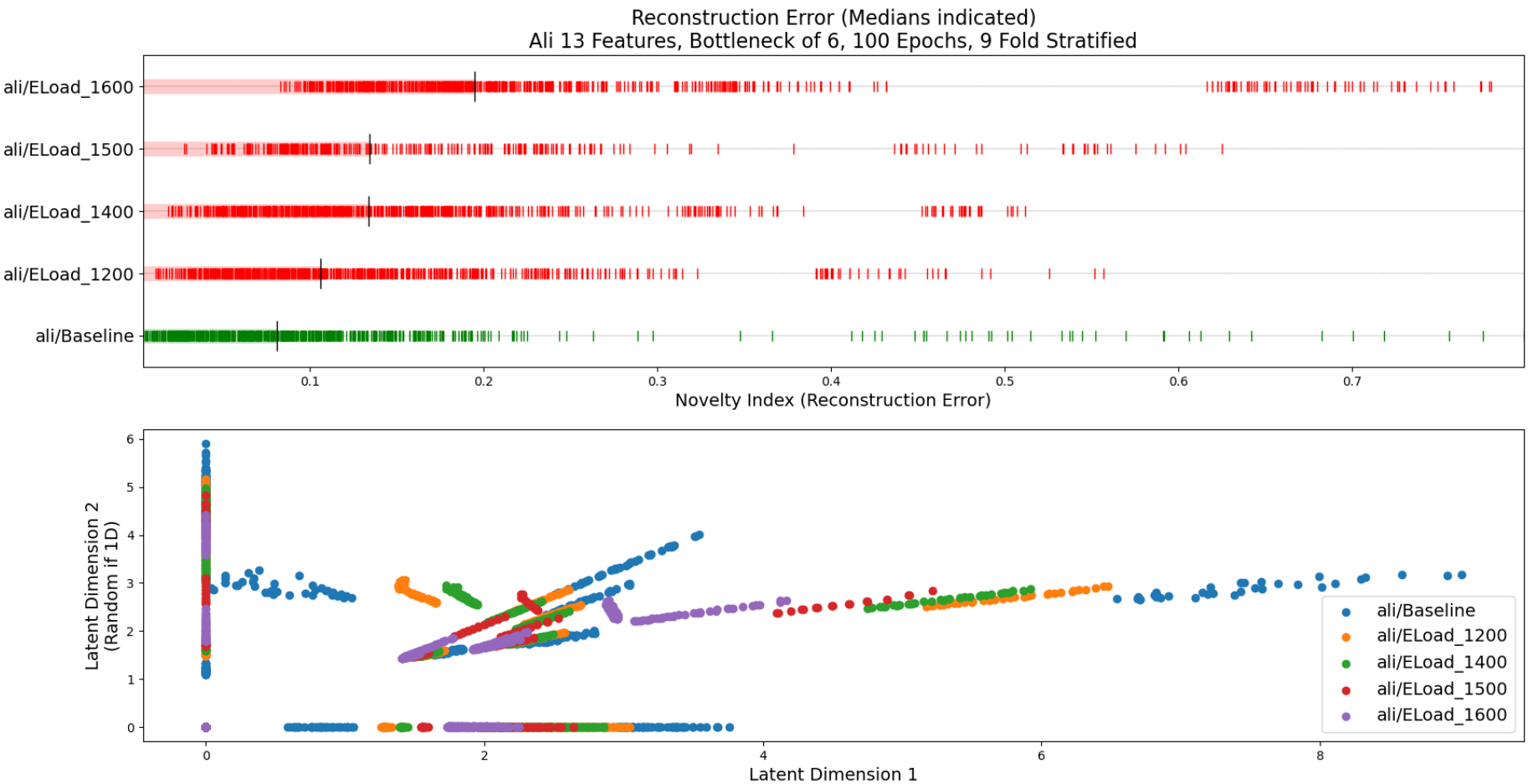
Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 4



Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 5

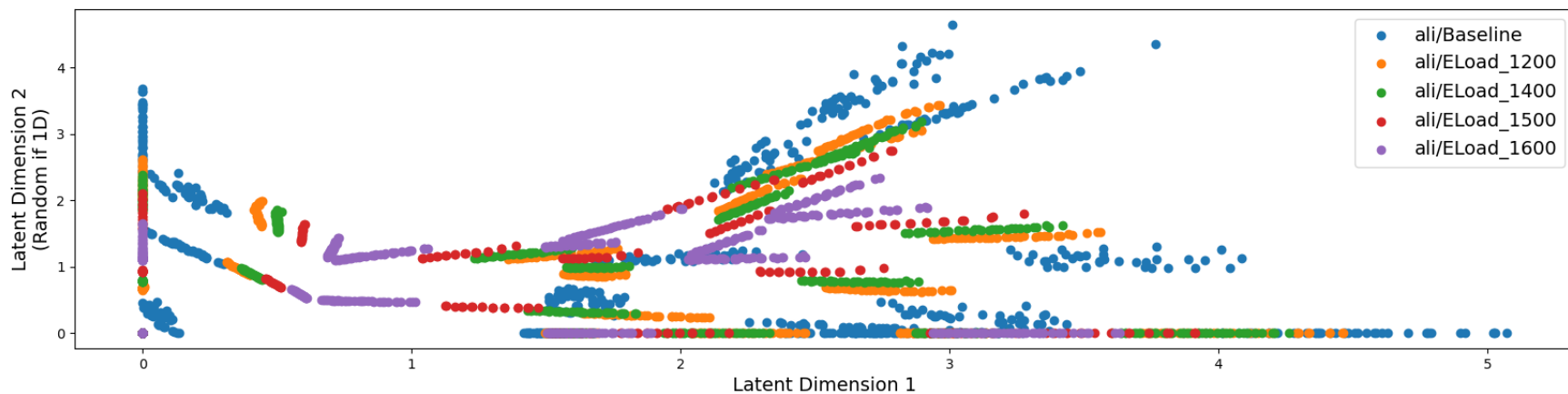
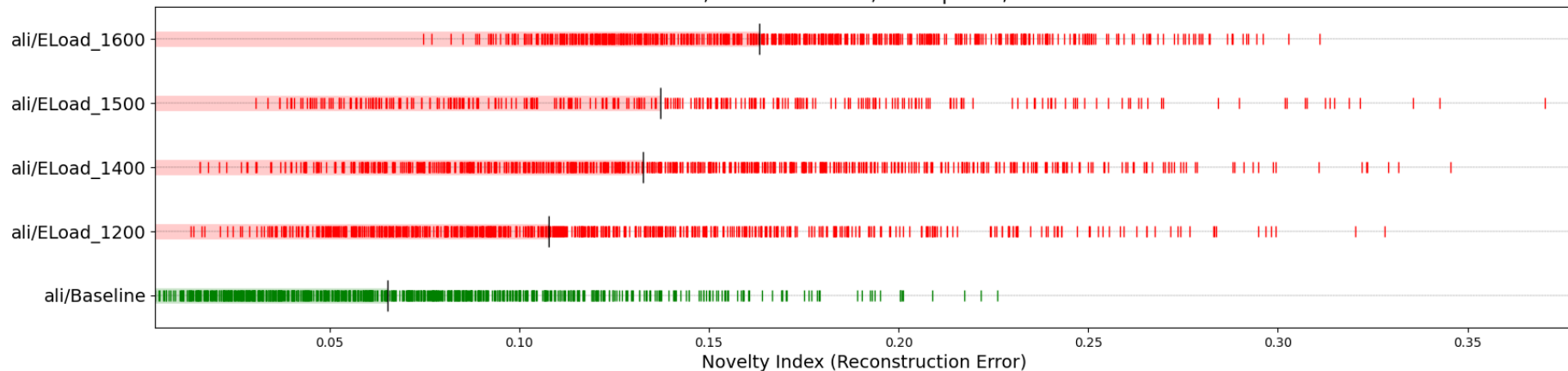


Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 6

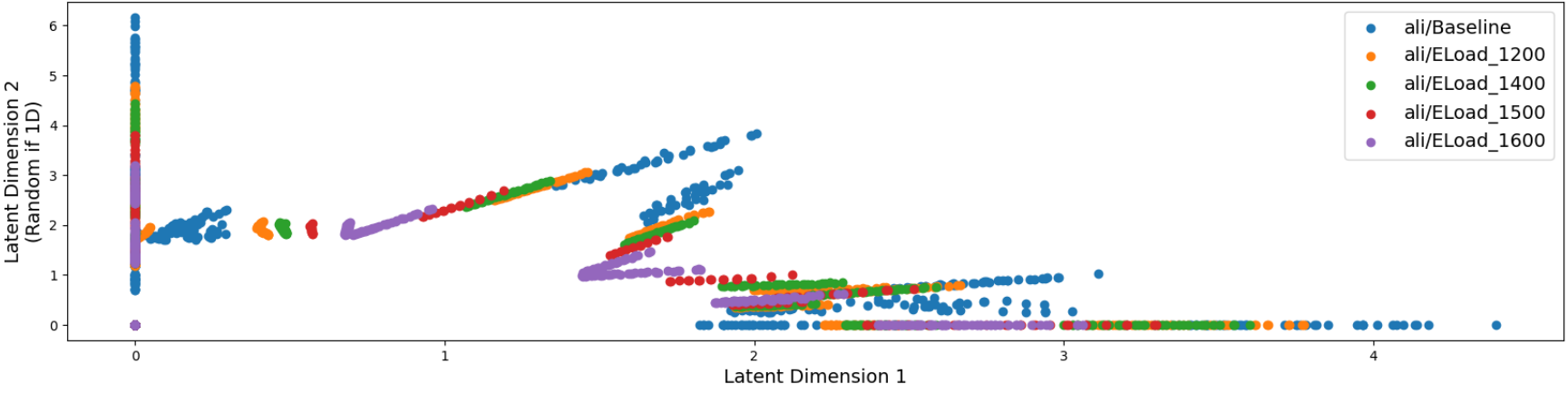
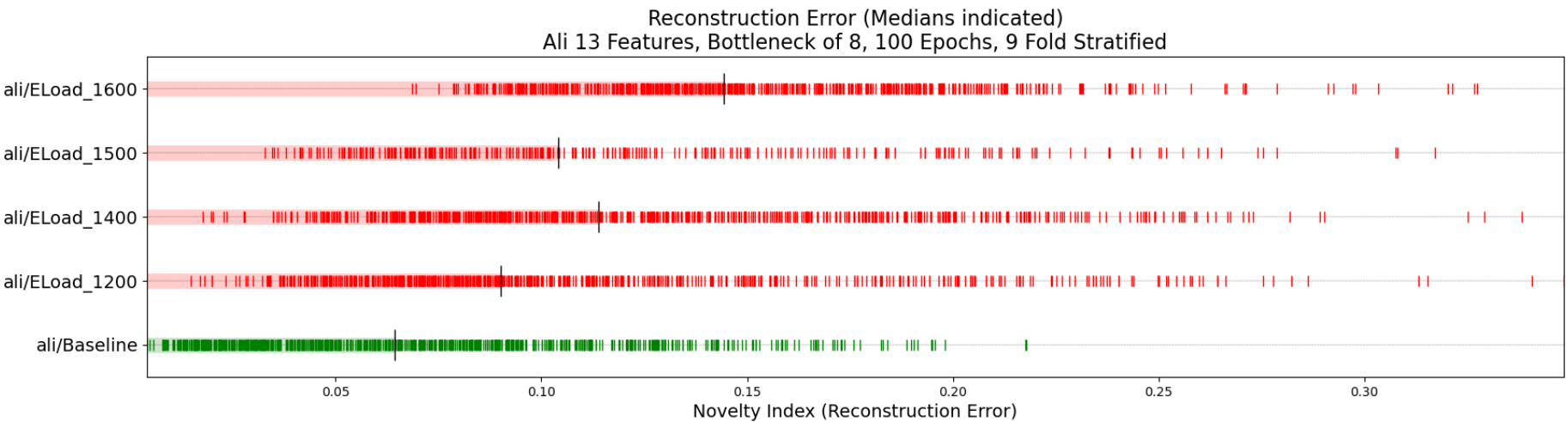


Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 7

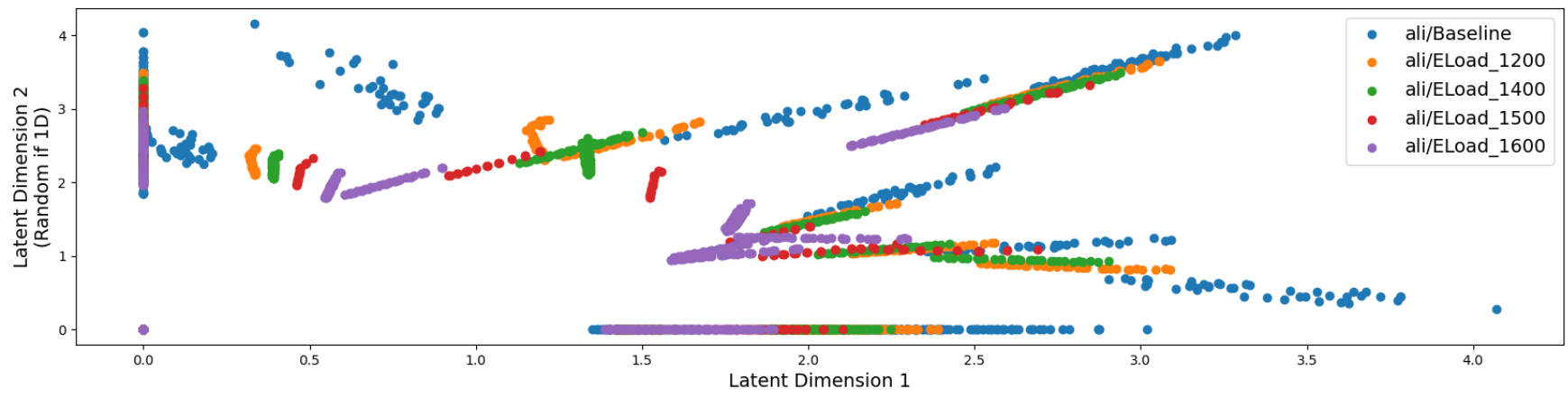
Reconstruction Error (Medians indicated)
Ali 13 Features, Bottleneck of 7, 100 Epochs, 9 Fold Stratified



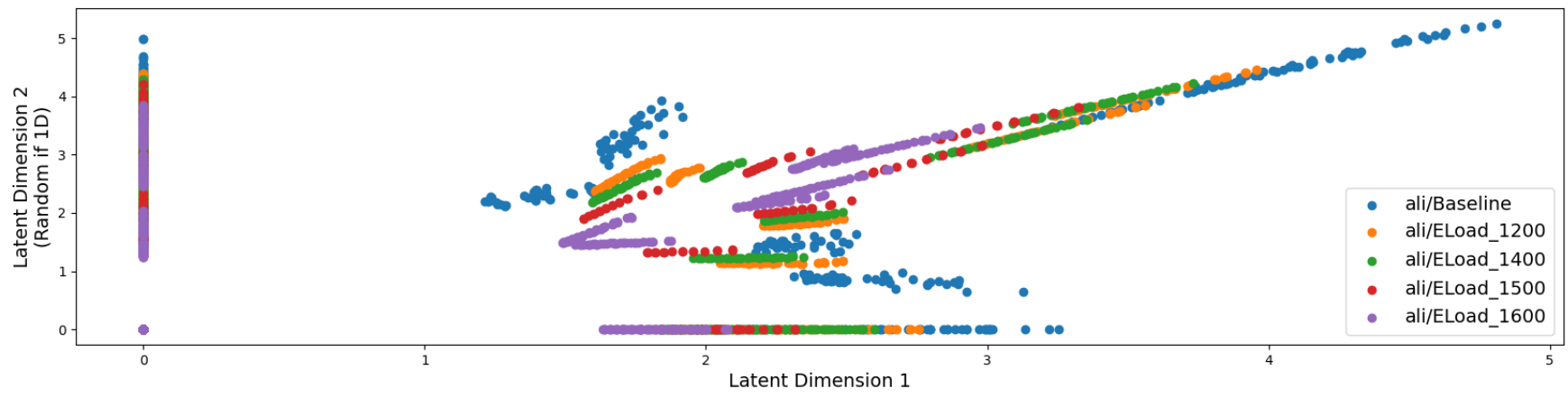
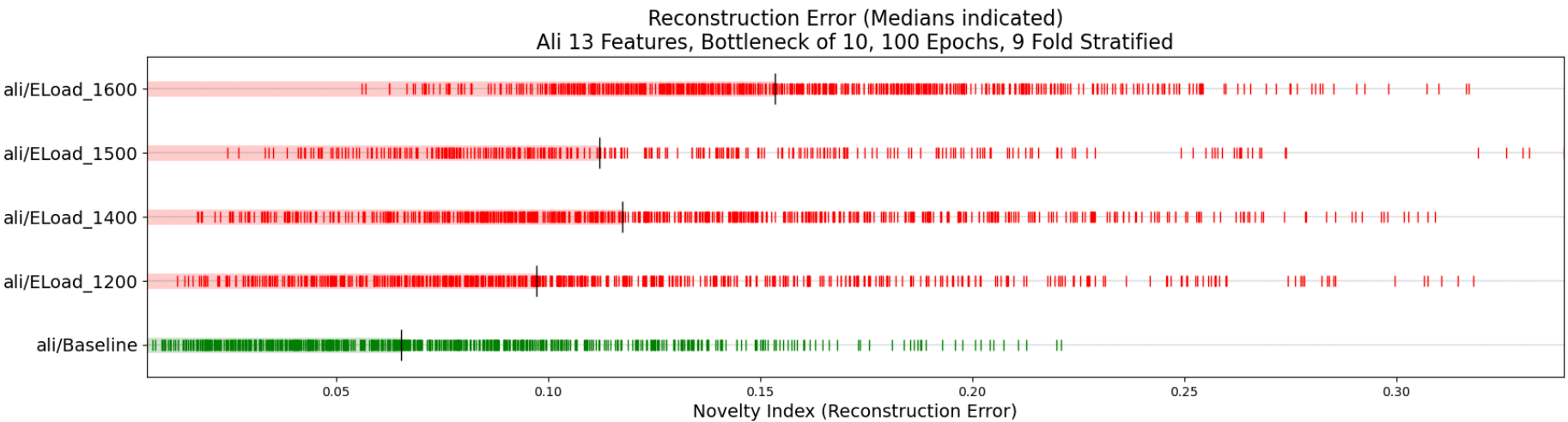
Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 8



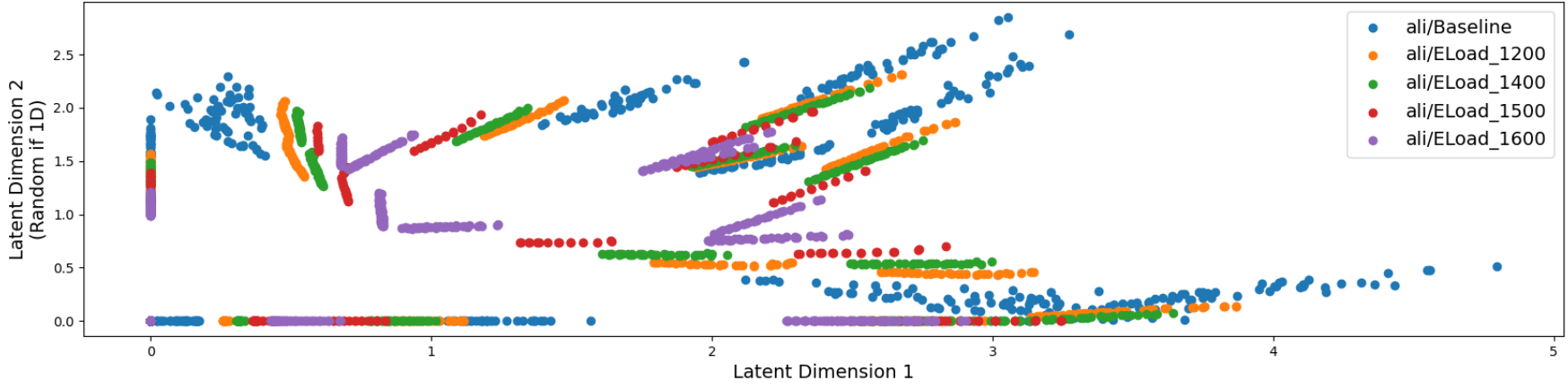
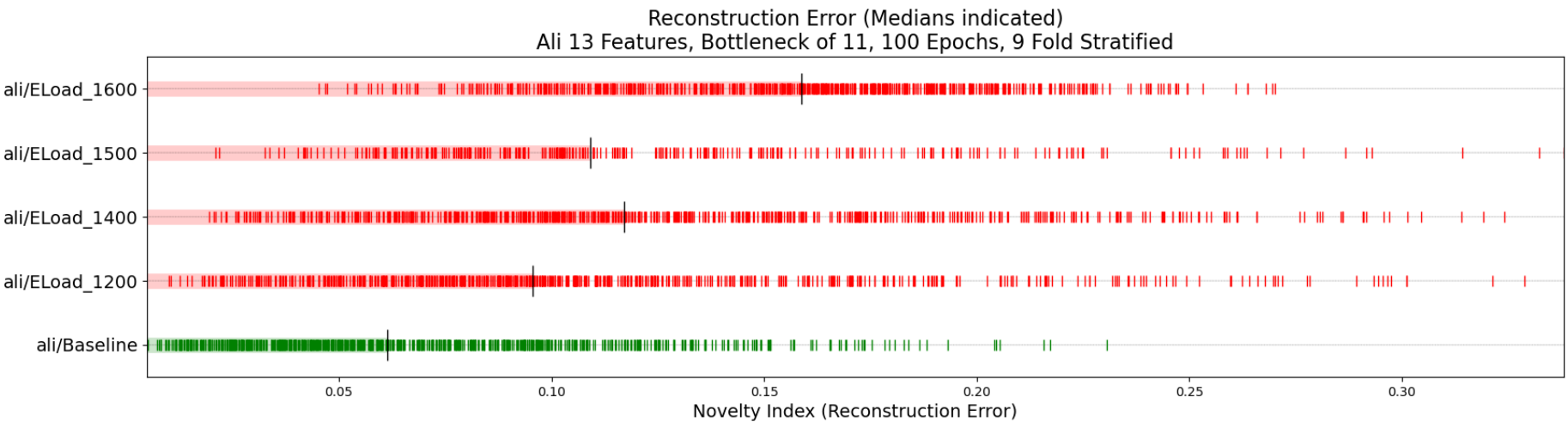
Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 9



Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 10



Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 11



Single-Actuator Data [Board 401] | Deep Auto-encoder Bottleneck of 12

